ADVANCED PLANNING AND SCHEDULING

IN THE UNITED STATES AIR FORCE DEPOT-LEVEL MAINTENANCE

THESIS

Shenn-Rong Shyong, Captain, Taiwan R.O.C. Army

AFIT/GLM/ENS/02-16

DEPARTMENT OF THE AIR FORCE
AIR UNIVERSITY

AIR FORCE INSTITUTE OF TECHNOLOGY

Wright-Patterson Air Force Base, Ohio

Report Documentation Page

Report Date	Report Type	Dates Covered (from... to)
02 Mar 2002	Final	Mar 2001 - Mar 2002

Title and Subtitle Advanced Planning and Scheduling in he United States Air Force Depot-Level Maintenance	**Contract Number**
	Grant Number
	Program Element Number
Author(s) Shenn-Rong Shyoung, CPT, Taiwan ROC Army	**Project Number**
	Task Number
	Work Unit Number
Performing Organization Name(s) and Address(es) Air Force Institute of Technology Graduate School of Engineering and Management (AFIT/EN) 2950 P Street, Bldg 640 WPAFB, OH 45433-7765	**Performing Organization Report Number** AFIT/GLM/ENS/02-16
Sponsoring/Monitoring Agency Name(s) and Address(es) Steven McBride, HQ AFMC/LGPA Mark Fryman, HQ, AFMC/LGXM WPAFB, OH 45433-5006	**Sponsor/Monitor's Acronym(s)**
	Sponsor/Monitor's Report Number(s)

Distribution/Availability Statement
Approved for public release, distribution unlimited

Supplementary Notes
The original document contains color images.

Abstract
The development of Expeditionary Aerospace Force (EAF) operations requires rethinking of many Air Force functions. A Logistics Transformation Team, comprising Air Force and KPMG Consulting Incorporation personnel, is leading much of this transformation work. The very first step of the transformation initiatives is demand planning, which is the process of translating the war fighters needs into executable logistics support plans and schedules. One important area that the demand planning focuses on is engine maintenance. This sub-mission is assigned to the F101 Engine Pathfinder Team, which is responsible for increasing the availability of the F101 engine. As part of the F101 Engine Pathfinder Teams effort, the focus of this thesis is to apply Modeling and Simulation (M&S), Response Surface Methodology (RSM), and Linear Programming (LP) to examine ways to reduce repair cycle time and work in process (WIP) investment for the F101 Low Pressure Turbine (LPT) rotor. We specifically evaluate a variety of job scheduling policies and spare levels.

Subject Terms	
Air Force Depot Maintenance, Advanced Planning and Scheduling, Spare Level Analysis, Modeling and Simulation, LP Optimization, Response Surface Methodology	
Report Classification unclassified	**Classification of this page** unclassified
Classification of Abstract unclassified	**Limitation of Abstract** UU
Number of Pages 106	

AFIT/GLM/ENS/02-16

ADVANCED PLANNING AND SCHEDULING

IN THE UNITED STATES AIR FORCE DEPOT-LEVEL MAINTENANCE

THESIS

Presented to the Faculty

Department of Operational Sciences

Graduate School of Engineering and Management

Air Force Institute of Technology

Air University

Air Education and Training Command

In Partial Fulfillment of the Requirements for the

Degree of Master of Science in Logistics Management

Shenn-Rong Shyong, B.S.

Captain, Taiwan ROC Army

March 2002

AFIT/GLM/ENS/02-16

ADVANCED PLANNING AND SCHEDULING

IN THE UNITED STATES AIR FORCE DEPOT-LEVEL MAINTENANCE

Shenn-Rong Shyong, B.S.
Captain, Taiwan ROC Army

Approved:

/s/ ____________________________________ __________
Lt Col John O. Miller, Advisor Date
Professor of Operation Research
Department of Operational Sciences

/s/ ____________________________________ __________
Major Stephen M. Swartz, Reader Date
Assistant Professor of Logistics Management
Department of Operational Sciences

Acknowledgements

First of all, I would like to express my sincere appreciation to my thesis advisor, Lt Col John Miller, for his guidance and support throughout the course of this thesis effort. I also would like to thank my academic advisor, Maj. Stephen Swartz for giving me the privilege to work through the hard stuff and discover what it means to do research, and my thesis sponsors, Mr. Mark Fryman and Mr. Steven McBride, who spent their valuable time explaining the processes and procedures of the LPT rotor maintenance.

Special thanks to my sponsors, Mr. and Mrs. Kinane, and members of International Affair Office, Mrs. Robb, Mrs. Jones and Mrs. Curtis, who can always be depended on for help. After all, I am indebted to my wife for knowing that my job is not an easy one, and doing everything she can to make it easier.

Shenn-Rong Shyong

Table of Contents

List of Figures

List of Tables

AFIT/GLM/ENS/02-16

Abstract

The development of Expeditionary Aerospace Force (EAF) operations requires rethinking of many Air Force functions. A Logistics Transformation Team, comprising Air Force and KPMG Consulting Incorporation personnel, is leading much of this transformation work. The very first step of the transformation initiatives is demand planning, which is the process of translating the war fighter's needs into executable logistics support plans and schedules. One important area that the demand planning focuses on is engine maintenance. This sub-mission is assigned to the F101 Engine Pathfinder Team, which is responsible for increasing the availability of the F101 engine. As part of the F101 Engine Pathfinder Team's effort, the focus of this thesis is to apply Modeling and Simulation (M&S), Response Surface Methodology (RSM), and Linear Programming (LP) to examine ways to reduce repair cycle time and work in process (WIP) investment for the F101 Low Pressure Turbine (LPT) rotor. We specifically evaluate a variety of job scheduling policies and spare levels.

ADVANCED PLANNING AND SCHEDULING

IN THE UNITED STATES AIR FORCE DEPOT-LEVEL MAINTENANCE

I. Introduction

Background

The period 1987 to 2001 has brought major change for the entire Defense Department and for DOD's depot maintenance program. The primary event that framed these changes was the end of the cold world and the associated military force structure downsizing. Three series of actions primarily shaped the depot maintenance environment. First, the base realignment and closure process has reduced the number of DOD's military depots from 38 to 19. Consequently, the services have generally not invested in depot plant equipment to establish new capability and advanced technologies. Second, as recommended in various studies, the Department has implemented a policy change placing increased reliance on defense contractors for depot maintenance. This policy shift to the private sector has most directly affected workloads for new and upgraded systems, which are largely going to the private sector. Third, depot maintenance personnel have been reduced by 59 percent, the third highest percent of any category of DOD civilian personnel. Today DOD has a smaller public sector depot structure, with less modern facilities and equipment and fewer maintenance personnel. The services continue to struggle to improve depot programs, processes, and operations

and make maintenance programs more efficient while meeting operational requirements. (Warren, 2001)

In September 1999, the Chief of Staff, United States Air Force (CSAF) directed a top-to-bottom review of base-level logistics processes. The review was titled the CSAF Logistics Review (CLR), and the purpose was simple: improve the Expeditionary Aerospace Force (EAF) combat readiness. Members from the headquarters staff, as well as operators and logisticians from all the major commands (MAJCOM), jointly participated in the review. Numerous circumstances contributed to the need for the CLR. The CLR methodology focused on MAJCOMs and wings. Air Staff and RAND Project Air Force researchers developed and refined the formal methodology, building a study matrix of evaluation metrics, and a list of potential targets of opportunity (ToO) for logistics process improvement. The ToO and MAJCOM inputs were grouped into four process focus areas: technical training and officer development, materiel management, contingency planning, and sortie production and fleet health management. (Zettler, 2001: 2-5)

Logistics Transformation Team

The redevelopment of Expeditionary Aerospace Force (EAF) operations requires rethinking of many Air Force functions. This includes the combat support system. To a large extend, success of the EAF depends on turning the current support system into one that is much more agile. In recognition of this, the Air Force has begun transforming the current support system to Agile Combat Support (ACS). It has designated ACS as one of the six essential core competencies for Global Engagement. A Logistics Transformation

Team, comprising Air Force and KPMG Consulting Incorporation personnel, is leading much of this transformation work. The Logistics Transformation Team was previously the Agile Logistics Team, which was previously the Lean Logistics Team (Tripp, 1996: 6). The main missions of the Logistics Transformation Team are as follows (Logistics Transformation, 2001: 3):

1. Re-engineer Air Force overarching Logistics System Processes—emphasis on end-to-end logistics system performance

2. Identify current initiatives and opportunities to increase performance and optimize costs—emphasis on short, medium and long term performance improvement

3. Develop change implementation plans—emphasis on execution; not just "another study"

4. Manage System-Level Logistics—emphasis on system level improvements

The very first step of the transformation initiatives is demand planning, which is the process of translating the war fighter's needs into executable logistics support plans and schedules. One important area that the demand planning focuses on is engine maintenance. This sub-mission is assigned to the F101 Engine Pathfinder Team, which is responsible for increasing the availability of the F101 engine by applying the following process: (See Figure 1)

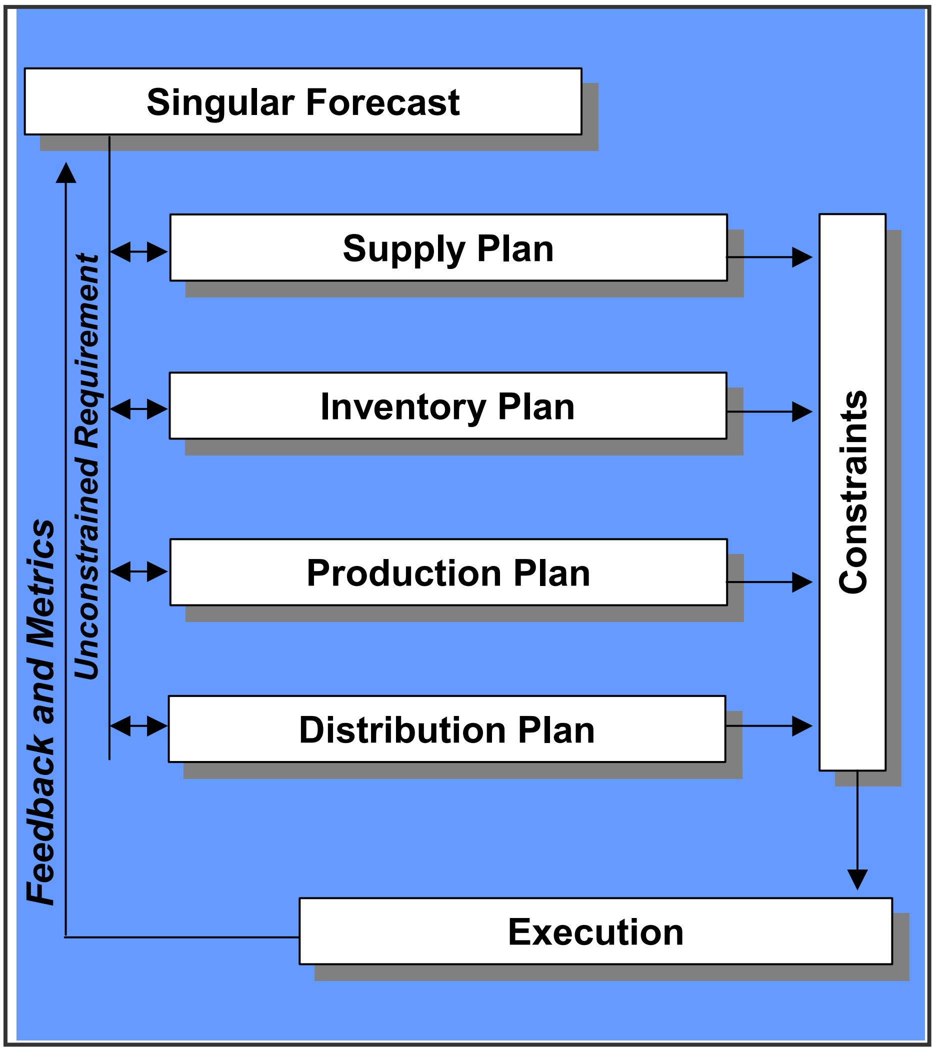
1. Develop a single forecast—utilized by entire team

2. Extrapolate forecast results into integrated functional plans

3. Enable re-planning using feedback on constraints

4. Enable successful collaboration

As part of the F101 Engine Pathfinder Team's effort, the focus of this thesis is to apply Modeling and Simulation (M&S) to examine ways to reduce repair cycle time for the F101 Low Pressure Turbine (LPT) rotor.



(Adapted from Logistic Transformation—APS Overview)

Figure 1. Linking Plans and Execution

Advanced Planning and Scheduling

Advanced Planning and Scheduling (APS) systems have been recognized by the Logistics Transformation Team as the most capable tools for creating optimized plans that improve entire Air Force logistics system performance. APS software systems are usually part of or integrated with a manufacturer's Enterprise Resource Planning (ERP) system, which is the direct descendant of and successor to Material Requirements Planning (MRP) and Manufacturing Resource Planning (MRPII). These tools enable fine-tuning of production and related activities with automatic updating of schedules as orders, resources, and constraints change. Planning and scheduling functions in an APS system support (but do not control) enterprise decision-making and production activities at the operational level, and at tactical and strategic levels over medium- to long-term periods. Together, when appropriate and where suitability linked, the combination of APS with e-business communications enables timely practices such as collaborative supply-chain actions, short-run production fulfillment, and crucial projections of new business feasibility. (Schultz: 2000, 29)

Following are the current essential steps identified by the Logistics Transformation Team for implementing APS systems (Logistics Transformation, 2001: 20):

1. Establishing an APS Prototype
    a. Focus on core functionality in an Air Force environment
    b. Build on Demand Planning Pathfinder groundwork—F101 Engine
    c. 12 month timeframe

2. Objectives: Test and evaluate COTS APS software; support an implementation decision by Air Force leadership.

    a. Identify and assess APS capabilities and limitations

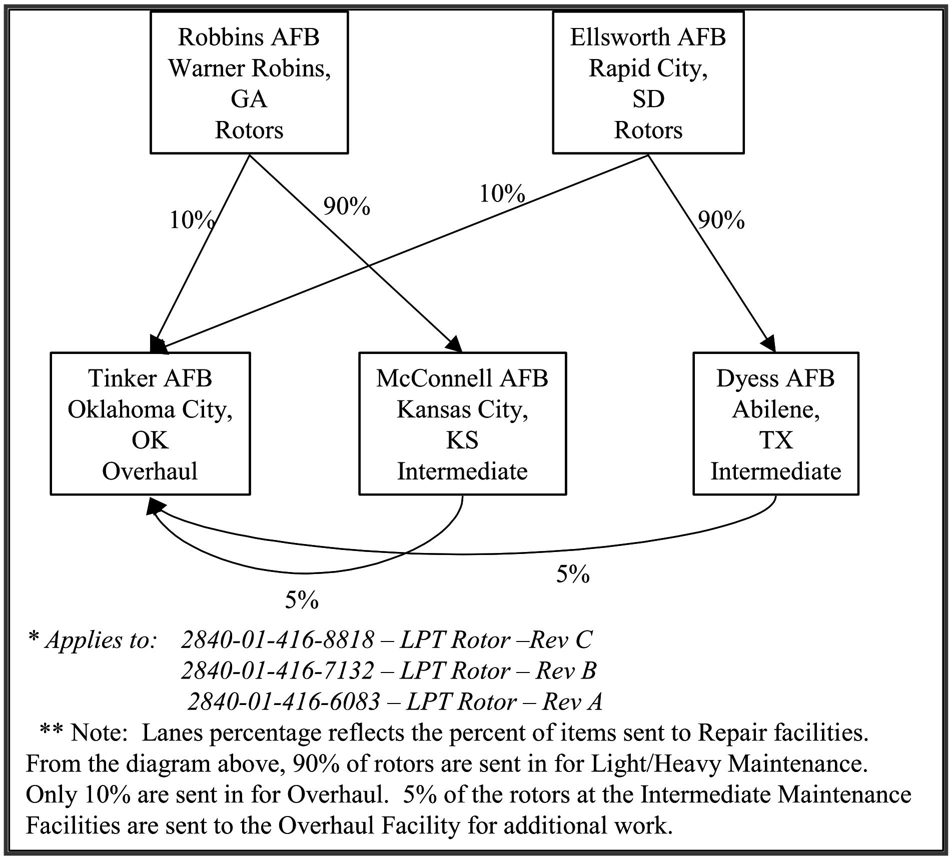
    b. Examine fit with legacy systems, planned IT initiatives and C2 structure

    c. Implementation parameters

The Air Logistic Center (ALC) Environment

Within the Air Force, the management of high-cost inventory items (those that would be considered class A items under ABC inventory control) is handled in a reparable-item pipeline. A reparable-item inventory system is a system used for controlling items that are generally very expensive and have long acquisition lead times. Hence, it is more economical to design these items so they are repaired after they fail, rather than treating them as consumable items. Over time, equipment malfunctions occur due to the failure of a specific item internal to the equipment. A corresponding serviceable item is then obtained from an inventory location and installed on the malfunctioning equipment, thereby restoring it to full operational capability. The failed item is tracked as it is shipped to the repair facility, scheduled for repair, and subsequently shipped in a serviceable condition back to an inventory location (Larvick, 2000: 2). The Air Force performs the majority of weapon system maintenance at two levels. The lower of the two levels is the intermediate maintenance; the upper level is the Air Logistic Center (ALC), or depot maintenance, where more complex repairs are accomplished. When a reparable part malfunctions at a base, it is sent to either the intermediate depot or the overhaul depot for repair. In the meantime, a serviceable part is

sent to the base immediately if available, to replenish stock. The defective part, upon arrival at the intermediate depot or the overhaul depot, enters a pool of items waiting to be repaired and returned into serviceable stock. The process for the LPT Rotor is illustrated in Figure 2.



(Adapted from Tinker APS Demo Components, 2001: 11)

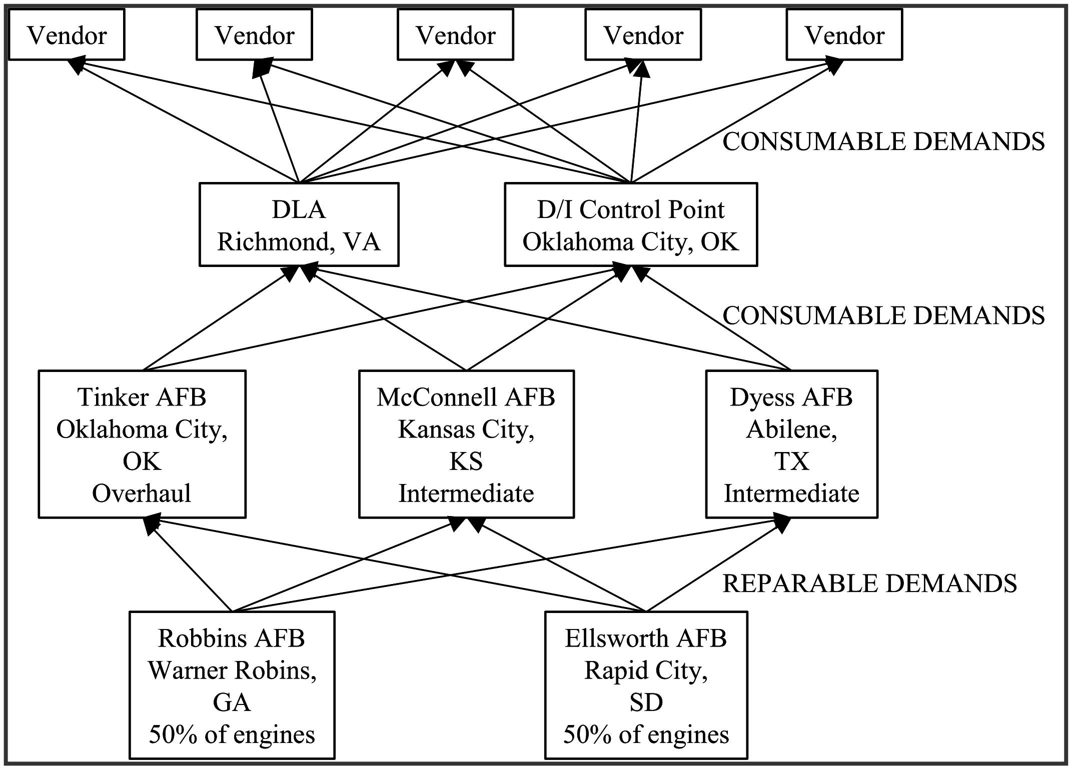
Figure 2. Flight Line Rotor to Repair

Intermediate depot tasks are performed by mobile, semi mobile, and/or fixed specialized organizations and installations. At this level, end items may be repaired by the removal and replacement of major modules, assemblies, or piece parts. Scheduled maintenance requiring equipment disassembly may also be accomplished. The mission is

to provide onsite maintenance to facilitate the return of the system to its full operational status on an expedited basis. (Blanchard, 1992:115)

Overhaul depot constitutes the highest type of maintenance, and supports the accomplishment of tasks above and beyond the capabilities available at the intermediate depot. Physically, the depot may be a specialized repair facility supporting a number of systems/equipments in the inventory or may be the equipment manufacturer's plant. Depot facilities are fixed and mobility is not a problem. Complex and bulky equipment, large quantities of spares, environmental control provisions, and so on, can be provided if required. The high volume potential in depot facilities fosters the use of assembly-line techniques, which, in turn, permits the use of relatively unskilled labor for a large portion of the workload with a concentration of highly skilled specialists in certain key areas such as fault diagnosis and quality control. The depot level of maintenance includes the complete overhauling, rebuilding, and calibration of equipment as well as the performance of highly complex maintenance actions. (Blanchard, 1992:116)

From an inventory perspective, depots need consumable parts to accomplish repairs in response to base demands. Under current DoD policy, consumable parts are provided from two sources: the Defense Logistic Agency (DLA) and the Depot/Inventory (D/I) Control Point. Considering the entire inventory hierarchy, reparable failures at the base level drive depot repairs. The level of repair activity at the intermediate and overhaul depots then creates a demand for consumable parts, which is used to place replenishment orders to DLA and D/I Control Point. The inventory process is shown graphically in Figure 3.



(Source: Tinker APS Demo Components, 2001: 12-14)

Figure 3. Flow of Demand for Consumable Parts

Tinker Air Force Base—Oklahoma City Air Logistics Center

Tinker's mission is to acquire and sustain the world's best aviation systems in partnership with the war fighters and suppliers to ensure the USA's air power is ready for war, contingencies and peacekeeping operations. Tinker is the only ALC in the Command with dual runways, critical necessities in supporting alert missions for the Navy, Air Combat Command, and the Air Force Reserves. Oklahoma City ALC is much more than a maintenance depot. The ALC provides four key elements of integrated weapon system support - program management, engineering, supply chain management and depot maintenance - for the United States Air Force, Navy and many other

customers. The ALC is responsible for integrated support of an inventory of 2,261 aircraft valued at almost $59B (Warren, 2001).

Problem Statement

The readiness of Air Force weapon systems is directly tied to parts availability. This research focuses on depot maintenance and examines the selection of an inventory management system to more effectively support the determination of material requirements for maintenance and repair.

Research Objectives

The primary objective of this research is applying simulation modeling to test the impacts various APS strategies, such as queuing policy and spare implementation, could have on the depot repair cycle for F101 LPT rotor, as a means to reduce its repair cycle time and work in process (WIP) investment.

Research Questions

To achieve the research objectives, specific research questions must be addressed. They are listed below chronologically, in terms of the order of research conducted.

1. What type of model is most appropriate for conducting this research study?
2. Is the current system only dedicated to LPT rotor repair? If not, how to abstract the LPT rotor repair processes from the current system?
3. Does the abstracted model well represent the realistic LPT rotor repair process?

4. Could use of APS reduce depot repair cycle time and WIP investment for the F101 LPT rotor?

Methodology Overview

The primary tool used in this research is simulation modeling. Due to the nature and complexity of the problem, simulation has been determined to be superior to other tools. A comparison of the competing APS inventory management models, based on the LPT Rotor scenario, will be conducted using simulation. Results will be analyzed using traditional statistical techniques to determine significant differences. In addition, various simulation parameters will be systematically modified to analyze the effects of different policies on system performance. The methodology used in this research will consist of the following steps:

1. Conduct a literature search of books, magazine articles, and other library information resources.

2. Meet with the AFMC Depot Maintenance Analysis personnel. Discuss current practices, and collect data on current material flows.

3. Identify commercial software packages for simulation and modeling analysis.

4. Prepare a baseline assessment to document the current repair processes of the overhaul depot for the LPT rotor at Tinker AFB.

5. Identify measures of performance and performance criteria through meetings.

6. Model the process and conduct simulation experiments.

7. Evaluate baseline model results with actual performance.

8. Prepare a comparison analysis.

Assumptions

1. The sample data selected are representative of the population of all the selected components.

2. The current system applies FIFO as the generic queuing policy within those relevant Resource Control Centers (RCCs).

3. The current system does not yet apply any spare to the LPT rotor repair process.

4. Foreign Military Sale (FMS) cases are negligible. (Components from different rotors can be put together after repaired.)

5. The lead times of those selected components are uniformly distributed between 1 and 2 days.

6. The routing times between those RCCs are negligible and set as 1 hour.

Scope/Limitations

The problem of analyzing the performance of maintenance systems in an environment such as a military depot is extremely complex. The sheer number of items stocked as well as the complexity of the repair process makes it difficult to conduct a broad study. As such, the scope of this research has been reduced for feasibility reasons. The first constraint imposed in this study is the use of data from a single engine component, LPT Rotor. The component under analysis was selected to represent the full range of parts problems experienced by an engine repair depot. This simplifies the simulation problem considerably, while maintaining most of the generality of results to other components and engine types.

Management Implications

As the Air Force Materiel Command (AFMC) considers including APS in its "standard suite" of computer systems for the Air Logistics Center, the results of this research can be invaluable. This study will analyze the LPT rotor repair process and recommend ways to improve it.

Organization of Research

In Chapter I, the background of the problem being study by the Air Force Logistics Transformation Team was first introduced. Next, the research objectives, questions that drove the study, an overview of the methodology, scope, and assumptions used were outlined. Finally, the limitations and management implications have been discussed to tie the results to the real world.

In Chapter II, an extensive review of applicable research is presented in the area of Modeling & Simulation and APS systems. Studies dealing specifically with Logistic Transformation are also reviewed to further clarify the extent of the problems. Chapter III lays the foundation of the simulation experiment and its methodology. A detailed description of the simulation models and experimental design is presented, as well as a description of the data collection methods employed. Finally, the plan for analyzing the data and formulating the results is presented. Chapter IV presents the data output from the simulation experiment, the statistical analysis of the data, and the results of the experiment. Finally, in Chapter V, overall conclusions are drawn from the results. Results are examined, and suggestions for implementation and procedural guidance are offered. Areas for potential future research are also offered.

II. Literature Review

Introduction

As part of the Logistics Transformation Team's effort on implementing APS to increase the availability of F101 LPT rotors, the focus of this thesis is to apply modeling and simulation (M&S) to examine ways to reduce repair cycle time for the F101 LPT rotor. We will begin this research with a brief discussion on the F101 LPT rotor, a review of the components of cycle time, and cycle time's subsequent impact on WIP investment and operational availability. Then, some related logistics research and methodologies applied will be discussed. Finally, some attributes of APS systems will be reviewed.

F101 LPT Rotor

Built by General Electric, the F101 engine was originally developed for the Advanced Manned Strategic Aircraft program, which became the B-1 bomber. The US B-1B is equipped with four 30,000 pound thrust class F101-GE-102 turbofan engines. Due to its largest internal payload of any current bomber and other unique attributes, the B-1B plays a critical role in the EAF combat readiness.

Designed with easier maintenance in mind, the F101 engine consists of four main modules, low-pressure turbine (LPT), high-pressure turbine (HPT), high-pressure compressor (HPC), and fan. This modularity is one of the essential aspects of its design, which facilitates easier and quicker repair of any component. The design also allows for easy exchange of modules from other engines or from stock of repair parts. Older engine

designs typically did not employ a modular concept, and hence require more maintenance man-hours for breaking down, repairing, and reassembling engines. The modularity feature of the F101 has proven to be convenient, especially considering the significant amount of maintenance required by the engine.

This research only focuses on the LPT module. There are 36 items that make up the LPT module; however, only those 18 significant items will be studied.

Repair Cycle Time Impact

Repair Cycle Time and WIP Investment

From the aspect of a repair line, a line's cycle time is the maximum time allowed for work on a unit at each station. If the time required for work elements at a station exceeds the line's cycle time, the station will be a bottleneck, preventing the line from reaching its desired output rate. The target cycle time is the reciprocal of the desired output rate (Krajewski and Ritzman, 1999: 428):

$$c = \frac{1}{r} \quad (1)$$

where c is cycle time, and r is desired output rate.

From the aspect of the depot, the overall length of the depot repair cycle is of vital importance for two basic reasons. First, timely depot repair of failed depot-level reparable items (DLRs) is essential to operational readiness and sustainability, and repair is typically the most responsive and least costly option for supporting customer requirements. Second, because of the high unit cost of DLRs, significant inventory investment results from the length of the depot repair cycle time (Kiebler et al, 1996).

Operational Availability

A primary reason for designing the F101 LPT Rotor to be constructed of modules was to take advantage of rotational pools to minimize aircraft down time. A rotational pool is a stockpile of spare parts (in this case a rotor module), which provides a spare to facilitate a quick repair of a broken engine. This allows the rotor to be repaired and reinstalled in the aircraft quickly and without waiting for the actual broken part to be repaired. The broken module is repaired later at a scheduled rate to maximize the productivity and efficiency of the maintenance facility. After repair, the module is returned to the pool stock and awaits issue for the next broken engine. (Stearns, 1998: 12)

The net result of this type of repair process is a reduction in repair cycle time, and ultimately higher aircraft availability, A_o, is achieved. This is expressed as

$$A_o = \frac{MTBM}{MTBM + MDT} \quad (2)$$

where *MTBM* is the mean time between maintenance and *MDT* is maintenance down time (Blanchard, 1998:81). Described relationally, as *MDT* becomes less, *MTBM* + *MDT* becomes less, and A_o becomes greater.

Overview of Logistics Modeling Approaches and Concepts

As evidenced from the literature, logistics modeling generally employs one of three approaches, optimization, heuristics, and simulation. While each approach has advantages and disadvantages, combining approaches could enable the advantages of one approach to offset the disadvantages of another approach.

Several advantages of optimization over the other approaches were identified: the best solution possible for a given set of assumptions and data is guaranteed, more realistic model structures can be handled correctly, and optimization economizes on data preparation and analyst time in setting up scenarios and evaluating their outcomes, and creative solutions never before considered can be uncovered since optimizing techniques will look at all the possibilities before selecting the best solution. Several disadvantages of optimization pointed out were: optimization cannot be used for all possible logistics decision problems, optimization suffers from the "black box syndrome" (not every logistics manager understands the workings of an optimization technique), the solutions do not prescribe the operating rules for implementing the results in a time span shorter than the periods used in the model, and optimization techniques are ill-equipped to handle problems that require data at the lowest level of detail. (Vashi and Bienstock, 1995: 197)

The second approach to logistics modeling, heuristics, is an effort to provide a working solution to the problem. Simply put, heuristics are rules of thumb that direct the user toward the best solution, but do not guarantee that it will be found. Heuristics provide ways of quickly finding satisfactory solutions to problems when methods such as simulation and optimization prove to be undesirable or impractical. (Vashi and Bienstock, 1995: 197)

The third approach to logistics modeling, simulation, derives its strength from its ability to incorporate stochastic situations, as opposed to the deterministic nature of optimization and heuristic procedures. Simulation technologies are capable of incorporating variance across either a dynamic or static planning horizon. In the depot environment, material flows, information flows, and processing techniques all have

significant impacts on the repair cycle time. The dynamics of the LPT rotor repair processes at Tinker ALC lend themselves to examination for potential improvements through the use of M&S techniques.

Logistics Research Applying Modeling and Simulation

For analysis within the Air Force depot environment, M&S has been widely applied in recent years. Kevin Mooney, a 1997 graduate of the Naval Postgraduate School (NPS), conducted his thesis research on improved aviation readiness and reductions in pipeline inventory investment through repair turn around time reductions related to the component repair processes internal to the Naval Aviation Depot (NADEP). Specific emphasis was given to the repair flow of a specific component from induction into the depot for repair to the ultimate availability for sale to customers in a ready-for-issue status. The research models the current NADEP repair process flow and simulates enhancements to the process flow. These enhancements identify savings of over $52,000 in repair pipeline inventory investment for the candidate item. The model and associated simulations provide NADEP with graphical and quantitative feedback that demonstrates the impact of process flow enhancements on repair turn around time and work in process inventory efficiency. (Mooney, 1997)

Dick E. Stearns, a 1998 NPS graduate, built a simulation metamodel for his thesis research used to determine initial rotational pool inventories for F404-GE-400 engine modules onboard a deployed aircraft carrier. The metamodel provides a means to address the problem for optimizing module inventory levels with operational availability. The simulation model is developed from real maintenance and usage data and provides a

detailed and accurate representation of the repair process. The results of this thesis can be generalized and applied to a wide family of weapon systems. (Stearns, 1998)

Kevin J. Gaudette, a 1998 AFIT graduate, conducted his thesis research on the impact of applying MRP logic in a remanufacturing environment. The experimental methodology involved the development of computer simulation models of Economic Order Quantity (EOQ) and MRP systems. Demand uncertainty, demand variability, and lead time variability were then varied at three levels each to develop a full factorial experimental design. The results were used to test EOQ and MRP using two different performance measures: average number of awaiting parts (AWP) days per repair and total annual inventory cost. The results lend support for the use of MRP in a remanufacturing environment. The number of AWP days was significantly reduced from that of the EOQ system, albeit at an increased inventory cost. When the two measures are combined, MRP appears to outperform EOQ in aggregate (Gaudette, 1998).

Simulation alone, however, provides merely the best answer of the solutions tried and is thus limited in it ability to find the "best" answer. As originally proposed by Vashi, Bienstock, and Mentzer:

> Applying response surface methodology (RSM) for optimization approach, with a minimum number of runs of the simulation model, the output from the simulation can be input to an optimizing approach to discern the optimal solution to the problem with respect to the relevant output variables. (Vashi et al, 1995: 198)

This research will take an approach that combines simulation and optimization techniques. Next, some concepts about M&S and optimization will be discussed.

Computer Simulation Concepts

Computer simulation refers to methods for studying a wide variety of models of real world systems by numerical evaluation using software designed to imitate the system's operations or characteristics, often over time. From a practical viewpoint, simulation is the process of designing and creating a computerized model of a real or proposed system for the purpose of conducting numerical experiments to give us a better understanding of the behavior of that system for a given set of conditions. The reason that simulation is frequently used as a tool to study the model is that the simulation model can be allowed to become quite complex, if needed to represent the system faithfully. Other methods may require stronger simplifying assumptions about the system to enable an analysis, which might bring the validity of the model into question. (Kelton et al, 2002: 7)

The majority of modern computer simulation tools implement a paradigm, called discrete-event simulation (DES). This paradigm is so general and powerful that it provides an implementation framework for most simulation languages, regardless of the user worldview supported by them (Altiok and Melamed, 2001: 13). In the Discrete Event Simulation (DES) paradigm, the simulation model possesses a state S (possibly vector-valued) at any point in time. A system state is a set of data that captures the salient variables of the system and allows us to describe system evolution over time. The state trajectory in time, $S(t)$, is abstracted as a step function, whose jumps (discontinuities) are triggered by discrete events, which induce changes in the system state at particular points in time. An essential feature of the DES paradigm is that "nothing" changes the state unless an "event" occurs, at which point the model typically

undergoes a state transition. The power and versatility of the DES simulation algorithm stems from the fact that the DES paradigm naturally scales to collections of interacting subsystems: one can build hierarchies of increasingly complex systems from subsystem components. In addition, the processing of any event can be as intricate as desired. Thus, both large systems as well as complex ones can be represented in the DES paradigm.

One of the most important issues facing a simulation analyst is that of trying to determine whether a simulation model is an accurate representation of the actual system being studied. In recent years there has been considerable interest in verification, validation, and a concept known as accreditation (VV&A). Verification is concerned with determining whether the conceptual simulation model has been correctly translated into a computer program. Validation, on the other hand, is the process of determining whether a simulation model is an accurate representation of the system, for the particular objectives of the study. Law and Kelton summarized some general perspectives on validation as follows (Law and Kelton, 2000: 265):

1. Conceptually, if a simulation model is "valid," then it can be used to make decisions about the system similar to those that would be made if it were feasible and cost-effective to experiment with the system itself.

2. The ease or difficulty of the validation process depends on the complexity of the system being modeled and on whether a version of the system currently exists.

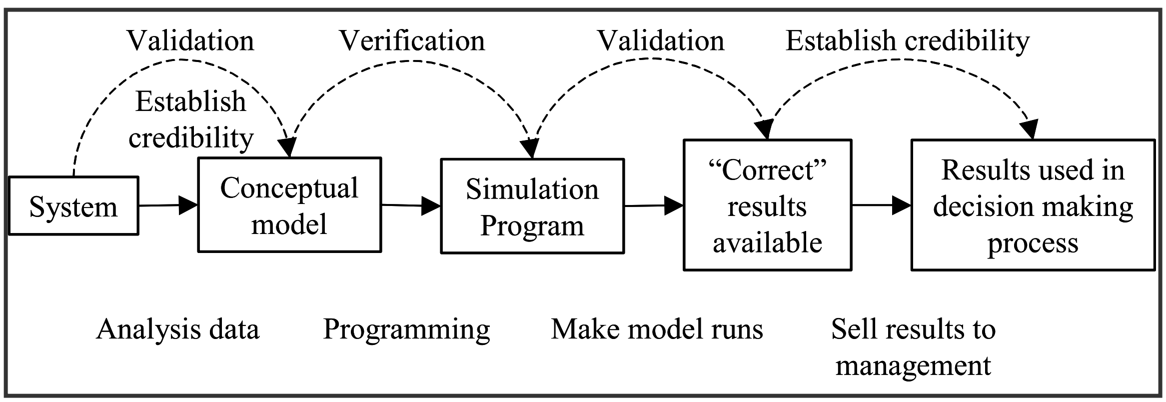
3. A simulation model of a complex system can only be an approximation to the actual system, no matter how much effort is spent on model building.

4. A simulation model should always be developed for a particular set of purposes.

5. The measures of performance used to validate a model should include those that the decision maker will actually use for evaluating system designs.

6. Validation is not something to be attempted after the simulation model has already been developed.

Accreditation is an official determination (perhaps by the project sponsor) that a simulation model is acceptable for a particular purpose. One reason that accreditation is considered necessary within the U.S. Department of Defense (DoD) is that many simulation studies use legacy models that were developed for another purpose or by another military organization. Besides VV&A, credibility is another important issue facing a simulation analyst. For this particular research study, credibility means that the sponsors or decision makers believe in the model results. The timing and relationships of validation, verification, and establishing credibility are shown in Figure 4.



(Adapted from Law and Kelton, 2000: 266)

Figure 4. Timing and Relationships of VV & Establishing Credibility

The working simulation tool for the models in this study is Arena 5.0. It is a simulation environment consisting of module templates, built around the SIMAN language constructs and other facilities, and augmented by a visual front end. Arena's fundamental modeling components, called modules, are selected from template panels, such as Basic Process, Advanced Process, and Advanced Transfer, and placed on a

canvas in the course of model construction. A module is a high-level construct, composed of SIMAN blocks and/or elements. Arena implements a programming paradigm that combines visual and textual programming.

Optimization Using RSM

RSM can be applied to any system that has the following key elements: (1) a criterion of effectiveness, which is measurable on a continuous scale (such as cost), and (2) quantifiable independent variables (both controllable and uncontrollable) that affect the system's performance. (An example of a controllable variable might be the selection of a particular scheduling or inventory policy, as discussed in the following section.) Given these conditions, RSM offers techniques for finding the optimum response of the system in an efficient fashion. In general:

$$y = f\,(x_1, x_2 \ldots x_k) + e \quad (3)$$

where the form of f is unknown and perhaps extremely complicated, and e is a term that represents other sources of variability not accounted for (Myers and Montgomery, 1995: 3). The preliminary objective of RSM is to approximate the function f (the response surface) in a relatively small region of the independent variables (x's) with some simple function. The simplest desirable functions generally are lower-order polynomials. If the approximating function is linear, then a "first order model" is fit to the response y. The response is modeled as follows:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_k x_k \quad (4)$$

If there is significant curvature present in the true response surface, then a "second order model" would be used:

$$y = \beta_0 + \sum_{j=1}^{k} \beta_j x_j + \sum_{j=1}^{k} \beta_{jj} x_j^{\ 2} + \sum_{i<j}\sum \beta_{ij} x_i x_j \qquad (5)$$

The second-order model is widely used in response surface methodology for the following reasons (Myers and Montgomery, 1995: 7):

1. The second-order model is very flexible.
2. It is easy to estimate the parameters in the second-order model.
3. There is considerable practical experience indicating that second-orders work well in solving real response surface problems.

Advanced Planning and Scheduling (APS) Overview

One of the better ways to explore APS is first to understand the attributes of MRP. The key inputs of a MRP system are a bill of materials database, master production schedules, and an inventory record database. Using this information, the system identifies actions that operations must take to stay on schedule, such as releasing new production orders, adjusting order quantities, and expediting late orders. An MRP system translates the master production schedule and other sources of demand, such as independent demand for replacement parts and maintenance items, into the requirements for all subassemblies, components, and raw materials needed to produce the required parent items. This process is called an MRP explosion (as depicted in Figure 5) because it converts the requirements of various final products into a material requirements plan that specifies the replenishment schedules of all the subassemblies, components, and raw materials needed by the final products (Krajewski and Ritzman, 1999:678). MRP, however, assumes certain ideal characteristics about the imperfect world of production and the plant floor (Gould, 1998:54):

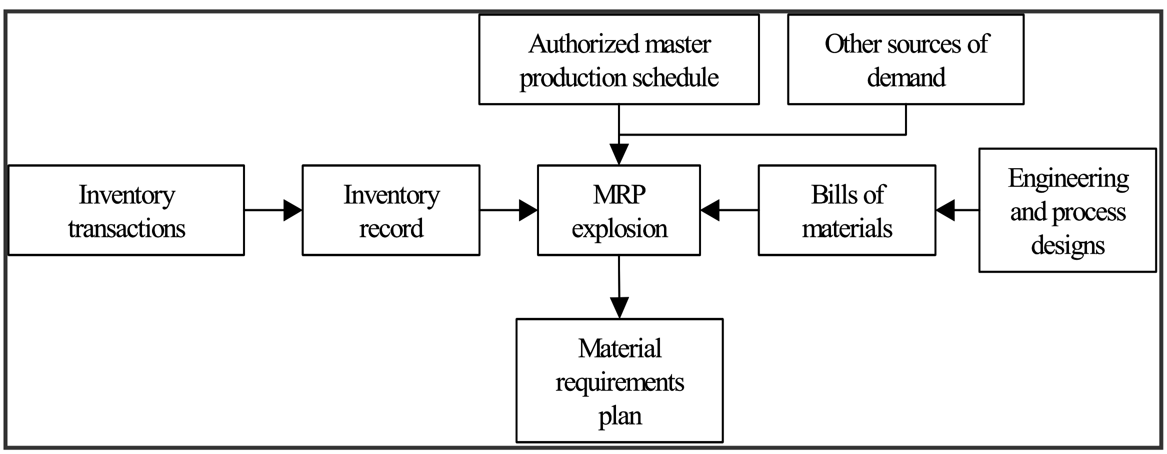
1. Infinite resources (machine capacity and labor) are always available and never change on weekly basis. MRP typically lets schedulers plan any job; the ones that can't be done become past due or violations of lead-time.

2. Material resources will arrive as scheduled in the right quantities. Any variances, or missed incoming shipments, were expedited manually until the next MRP run.

3. Customer orders and products have the same priority. MRP can't differentiate customer orders from orders for safety stock and forecasted orders. Generally, MRP just aggregates demand into lots, and outputs numbers that essentially say, "make all of these items."

4. Lead times (production and material delivery) are fixed or proportional to lot size.

5. Weekly buckets are good enough for scheduling purposes. The fact is that an MRP run took all weekend; so all a production planner could expect was a weekly schedule that was immediately out of date once printed.

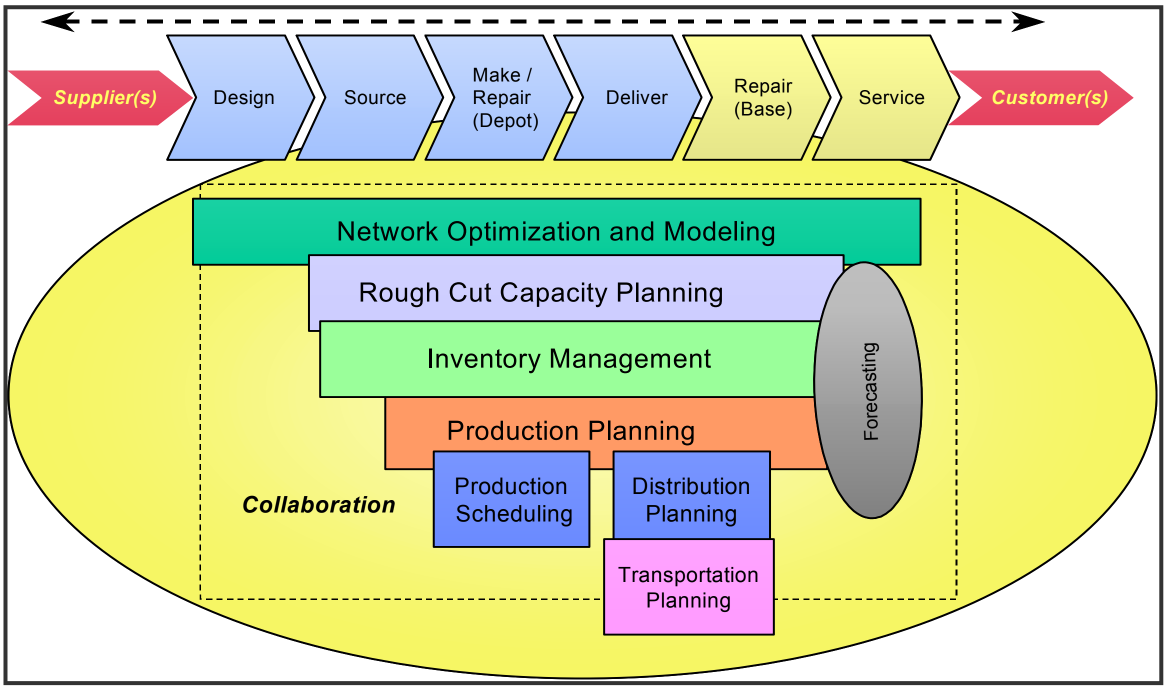


(Adapted from Krajewski and Ritzman, 1999:678)

Figure 5. MRP Requirements Plan Inputs

Since the very beginning, manufacturing management software has grown and evolved continuously, adding more capabilities and deeper functionality year after year. Because of changes in technology, APS can synchronize demands and constraints rapidly, using real-time customer and manufacturing data through electronic data

interchange (EDI). Although the perception of e-business's promise has, by large, outpaced its reality today in most manufacturing environments, the demonstrated benefits of APS systems make them a natural ally of e-business. APS vendors insist the systems will be more compatible with e-business as more development unfolds (Schultz, 2000: 29). Like any other manufacturing management software, APS is continuously evolving. Typical APS components are shown in Figure 6.



(Adapted from Logistic Transformation—APS Overview)

Figure 6. Typical APS Components

This research will focus only on inventory management using the following APS tasks as a starting point:

1. Manages time-phased product/material flow
    a. Using forecast, optimizes logistics system inventory
    b. Network wide visibility of stock locations

    c. Allocates critical inventory during supply shortages

2. Suggests optimal production and procurement plans

    a. Ability to fill planned and unplanned requirement

    b. Calculates and plans lead time to secure a product against a backorder

    c. Alternative sources/products

Summary

The F101 LPT rotor was briefly introduced at the beginning of this chapter. Then, the significance of depot repair cycle was recognized for two main reasons: operational readiness and WIP investment. The review of related logistics research revealed that a combination of M&S and optimization approach has becoming more popular. Vashi, Bienstock, and Mentzer proposed that the M&S/Optimization approach combines the advantages of simulation and optimization, thereby compensating for some of the disadvantages of both. This research, therefore, will apply this M&S/Optimization approach. In order to properly use M&S and optimization as the primary tools for this research, concepts about computer simulation, DES, VV&A, and RSM were discussed. As the working simulation tool, some important attributes of Arena 5.0 were introduced. APS was then briefly discussed. Since APS covers a very broad field, this study will focus only on some inventory management issues. In next chapter, the M&S/Optimization approach as well as a detailed description of the simulation models and experimental design will be presented.

III. Methodology

Introduction

This chapter discusses the experimental design and analytical methodology employed in this study. It begins with a general discussion of the issues and steps in designing an experiment, and then goes on to discuss the specifics of this study within that framework. Next, the problem statement is shortly revisited, followed by the descriptions of the simulation model. After the background on model logic is introduced, the relevant response variables and applicable factors and levels are discussed. To assure more credible results, issues about model verification and validation are discussed. Finally, the experimental designs for comparing different scheduling policies with different spare levels on the identified response variables are outlined.

Experimental Design

The guidelines for designing experiments suggested by Montgomery (Montgomery, 1991: 9-11) as well as the major steps for M&S proposed by Altiok and Melamed (Altiok and Melamed, 2001: 6-7) both are applied in this study. These two methods are quite similar with the M&S method specifying simulation as the major tool for performing the experiment. Table 1 shows the major steps of these two approaches combined. Steps 1 and 2 have already been discussed in chapter II; they will still be briefly revisited. This chapter focuses on steps 3, 4, 5, and 6, while step 4 will be introduced first because it provides some basic information for discussing the remaining steps. Steps 7 and 8 are conducted in Chapter IV. Practically, there is no such system that is only dedicated to LPT rotor repairing; thus, it is critical to abstract the LPT rotor repairing process from the

real system as the experiment platform of this study. Reasonable parameters for making valid model runs and analysis are discussed in Step 5—Model Validation and Verification.

Table 1. Combined Steps of Designing and Analyzing the Experiment

Step	Montgomery	Altiok and Melamed	Combined
1	Recognition of and statement of the problem	Problem Analysis and Information Collection	Recognition of and statement of the problem
2	Choice of factors and levels	Data Collection	Selection of the response variable
3	Selection of the response variable	Model Construction	Choice of factors and levels
4	Choice of experimental design	Model Verification	Model Construction
5	Performing the experiment	Model Validation	Model Validation and Verification
6	Data analysis	Designing and Conducting Simulation Experiments	Choice of experimental design (RSM)
7	Conclusions and recommendations	Output Analysis	Performing the experiment
8		Final Recommendation	Output Analysis (RSM)
9			Final Recommendation

Recognition of and Statement of the Problem

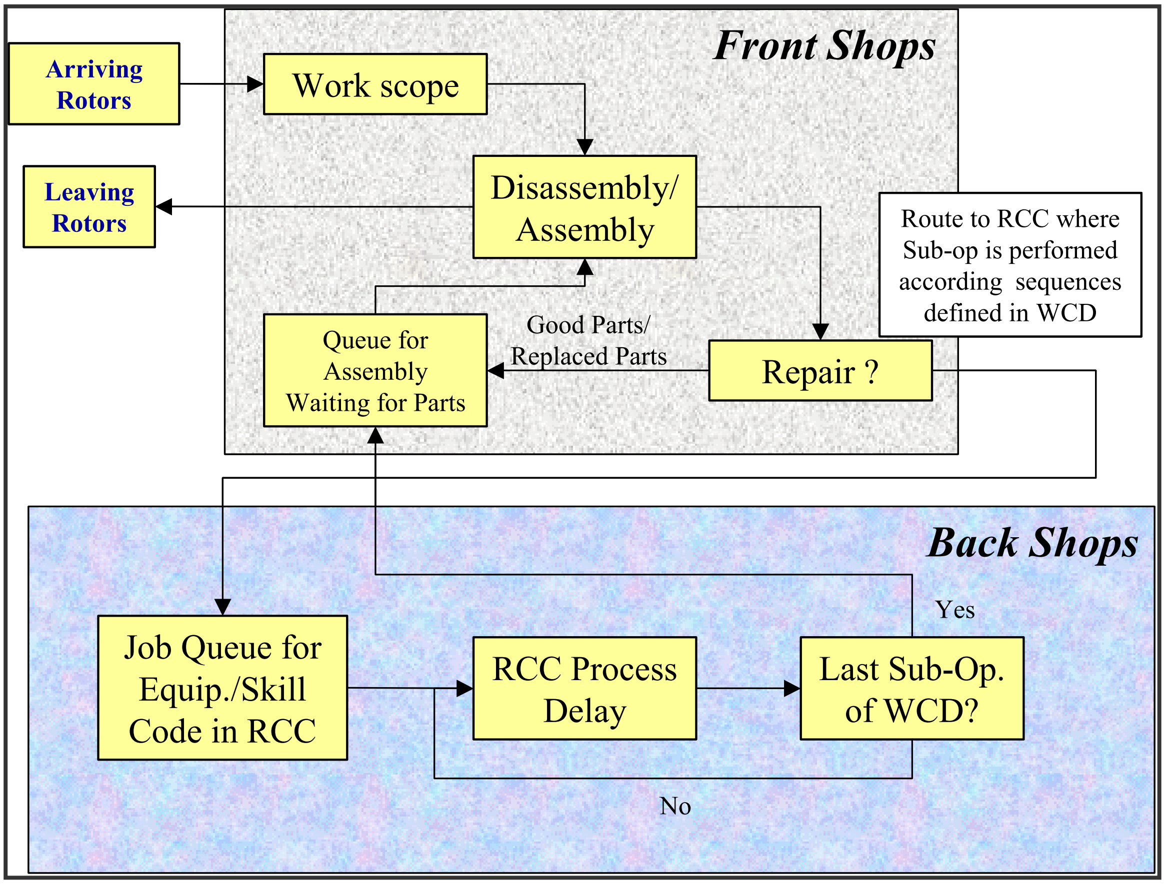
The primary objective of this research is applying simulation modeling to test the impacts various APS strategies such as queuing policy and spare implementation could have on the depot repair cycle for the F101 LPT rotor, as a means to reduce its repair cycle time and work in process (WIP) investment. While one queuing policy might be better than the other with different spare levels available, this study will apply M&S and optimization techniques to analyze the combined effect provided by these two factors and recommend a best combination of queuing policy and spare mix for the LPT rotor repair process.

Model Construction

The model overview is first discussed, and then followed by detailed model descriptions. The modeling process begins with a comprehensive identification of the system and components to be modeled. In order to ensure each aspect of the repair process is adequately incorporated into the model, it is important that the repair process is diagrammed using flow chart techniques (Figure 7). Without first visually illustrating the process in this fashion and validating each step, the overall process could be inaccurate and the model would not function as a useful tool for critical analysis. By utilizing both the flow diagram and the Work Control Document (WCD, Appendix A-1) as a framework, each step in the LPT rotor repair process is examined. The WCD outlines a repair plan in accordance with Technical Order specification, defines the sequential operations associated with a repair, specifies the RCC in which a sub-op is performed, and stipulates the equipment and labor skills used at a sub-op. A part repair is finished when all required sub-ops on the WCD have been completed and stamped by authorized mechanics (Gogg and others, undated: 1). Serviceable (repaired) parts are returned to the spare pool or the assembly station. Equipment, and labor skills shared among RCCs are summarized in tabular forms shown in Appendix A-2, A-3.

LPT rotors enter the repair process through front shops. There they are disassembled. Only those assemblies and components needing repair are routed to the back shop. Good or replaced parts remain in the front shops to be assembled into a rotor. Most parts needing repair are worked in the Propulsion Production Branch (LPPP) back shops. However, some accessory components are routed to the Accessories Division

(LIP) for repair. A few parts may be sent to private contractors for processing. This study only focuses on the repair in LPPP back shop.



(Adapted from Gogg and others, undated: 4)

Figure 7. LPT Rotor Repair Logic Flow

Some back shop RCCs are very specialized, performing only a few repair operations, while others carry out a wide range of activities. Some of the process back shops such as cleaning, heat-treat, and plating may receive significant workload from outside the LPPP organization. This non-LPPP workload may not be defined by a WCD, and it is also not within the scope of this study. Only in very special cases will the assembly process be delayed to await return of the exact part that was removed, so this study assumes that any set of eighteen different parts can be assembled as a LPT rotor.

Engine disassembly and assembly occur within the same location and use the same labor skills. Mechanics use the Inventory Tracking System (ITS) Assembly Structure generated from the LPT rotor disassembly to identify required parts for LPT rotor assembly. Serviceable parts are obtained from supply when they are not obtainable from within the shop. When parts become available, they are reassembled into a LPT rotor. The majority of delays during LTP rotor assembly are due to awaiting parts. This occurs when serviceable parts are unavailable but required by a front shop for assembly (Gogg and others, undated: 2).

The working model of this study consists of two parts, the front shop and the back shop. The front shop consists of disassembly and assembly station, and the back shop consists of those 20 RCCs involving with LPT rotor repair:

In the front shops (Appendix B-1), LPT rotors first arrive at the disassembly station (Appendix B-2) where a rotor is disassembled to 18 parts. According to the percentages shown in Table 2, good or replaced parts remain in the front shops waiting to be reassembled into a LPT rotor. Before a part needing repair is sent to the back shop, its spare level is checked (Appendix B-3). If there is a spare, the spare is directly sent to the assembly station, and the original part is marked as a spare-replaced part and sent to the back shop for repairs. After a spare-replaced part is repaired, it is looped back to the spare pool instead of the front shop for assembly. If there is no spare, the original part is then sent to the back shop directly.

Once a part repair is finished, the part is sent to the assembly station (Appendix B-4). Its flow time is first recorded (Appendix B-5), and then it is assigned an assemble-sequential index (Appendix B-6). A part’s repair cycle is the time period from right after

it is disassembled from a rotor to its entering of the assembly station. The assemble-sequential index is used for identifying a set of 18 different parts. This is a separate index for each of the different part types. Each part is assigned the next sequential value of this index once they arrive to the assemble station. Thus, once there is one part from each of the 18 types, they can be batched and assembled. Note that the assemble-sequential index is used only at the assemble station for batching parts, and is different from the arrival index, which is only used by a certain queuing policy at the back shop for indicating process priorities. The arrival index will be discussed later on in the Choice of Factors and Levels section.

Table 2. Part Repair and Replace Percentages

Part ID #	Nomenclature	Repair %	Replace %	Good %
1	DISK, STG 1 LPT	75	20	5
2	SEAL ROTATING	95	0	5
3	#2 DISK	95	0	5
4	MATING RING	95	0	5
5	#1 BLADE		100	
6	SEAL, FRT LPT AIR	78	17	5
7	SHAFT LPTR	95	0	5
8	SPCR, LOWER SEAL	95	0	5
9	RETAINER, LPT #2	37	58	5
10	SUPORT, LPT CONE	95	0	5
11	RETAINER, LPT #1		100	
12	#4 SEAL HSG-LPT	95	0	5
13	#2 BLADE		100	
14	NUT #1	95	0	5
15	VENT, CENTER	95	0	5
16	NUT #2	95	0	5
17	SEPARATOR	95	0	5
18	SLEEVE, LPTR DAMPER	95	0	5

(Adapted from Tinker APS Demo Components, Depot Normal Overhaul)

For the back shop (Appendix B-7), there are 20 RCCs involved with the LPT rotor repair process (Table 3). Normally, parts are routed between RCCs via a conveyor system, by forklift, by bicycle or hand carried. In this study, the routings among RCCs

are simplified since they do not provide significant effect on the analysis of this study. The route times among all the RCCs are set as 1 hour. The distribution of each RCC's process time of each type of part is approximated according to its average flow time and sequential operations defined in the WCD. See the Model Validation and Verification section for more details.

Table 3. RCC Description and Schedule

RCC	RCC Description	Shifts Worked
MEPBE	SURFACE PREP BLADES	TWOSHIFT
MEPBF	BLADE FPI/NDI INSPEC	ONESHIFT
MEPBG	REWRK FAN/TURB/COMP	TWOSHIFT
MEPBH	BLADE CLEAN/SURF ENH	TWOSHIFT
MEPCA	CHEM CLEAN ENG COMP	TWOSHIFT
MEPCB	INSP/WCD/DECOS ENG C	TWOSHIFT
MEPCG	BLAST/SURFACE PREP	TWOSHIFT
MEPCH	PLATING A/C ENG PART	THREESHIFT
MEPCI	PLASMA SPRAY	TWOSHIFT
MEPCJ	HEAT TREAT SHOP	THREESHIFT
MEPCN	X-RAY/TCR NDI/ECII	THREESHIFT
MEPME	SEAL SHOP	THREESHIFT
MEPMK	HOURGLASS/HEAVY MACHINING	TWOSHIFT
MEPMP	CNC MACHINING	THREESHIFT
MEPMR	CASE REWORK	THREESHIFT
MEPMS	TURBINE SHAFT	ONESHIFT
MEPMV	TURBINE DISK/SHAFT	THREESHIFT
MEPMW	L/S-H/S COMPRESSOR	THREESHIFT
MEPWB	GENERAL WELDING	THREESHIFT
ONESHIFT: From 0700 to 1530. TWOSHIFT: From 0700 to 2400. THREESHIFT: From 0000 to 2400		

For ease of modeling RCCs are clustered into 4 groups. MEPBE, MEPBF, MEPBG, and MEPBH are clustered in Group 1 (Appendix B-8). MEPCA, MEPCB, MEPCG, MEPCH, MEPCI, MEPCJ, and MEPCN are clustered in Group 2 (Appendix B-9). MEPME, MEPMK, MEPMP, MEPMR, MEPMS, MEPMV, and MEPMW are clustered in Group 3 (Appendix B-10). MEPWB and MEPWG are clustered in Group 4 (Appendix B-11). The logic within each RCC is nearly identical. Using MEPBE (Figure 8) as an example, at the first decision node the availability of a dummy resource—*shift*

key is checked first. Since a RCC is not a resource, a schedule cannot be implemented on a RCC directly. The dummy resource—*shift key* is thus applied. By implementing a schedule on the *shift key*, the RCC can thus only be entered during its operating hours defined in the schedule of *shift key* (Table 3). There are only two types of *shift key*; one for one-shift RCCs, the other for two-shift RCCs. Three-shift RCCs, such as MEPCH (Figure 9), do not need a *shift key* resource since they operate 24 hours a day.

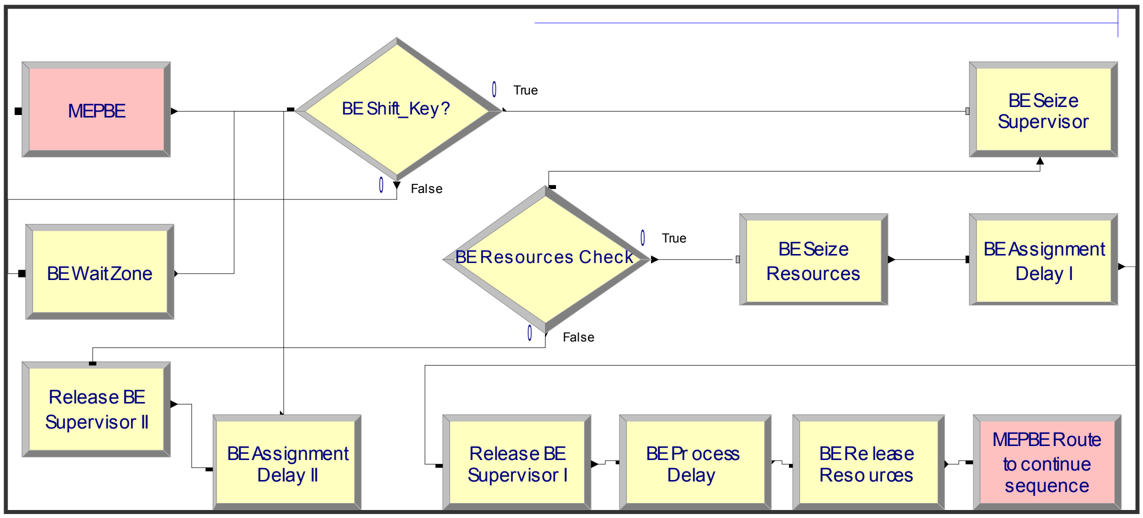


Figure 8. MEPBE RCC (Two Shift)

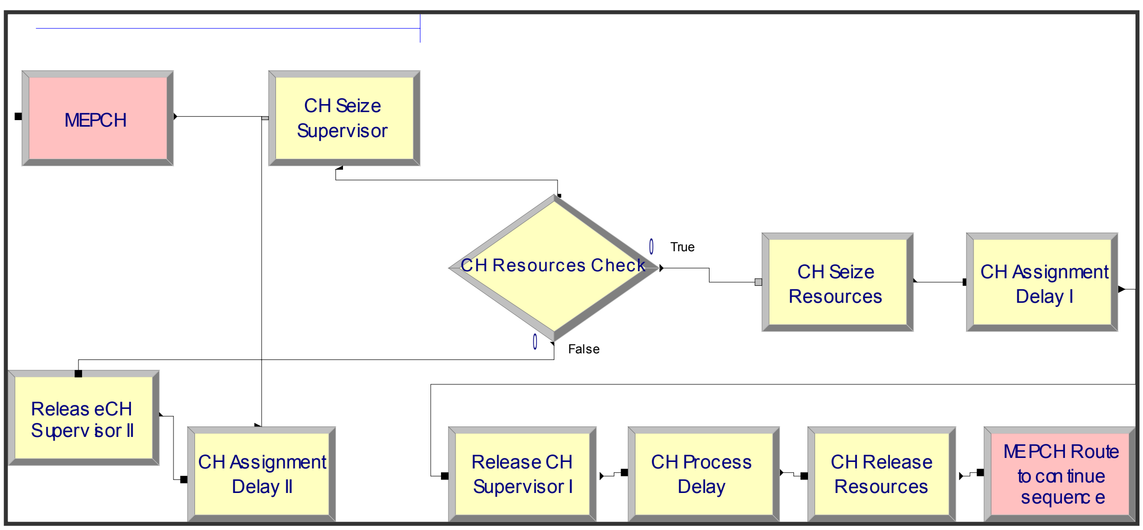


Figure 9. MEPCH RCC (Three Shift)

It is assumed that there is a supervisor within each RCC. The supervisor is responsible for queuing the parts according to the selected queuing discipline. Parts might require different equipment and labor skills within the same RCC, and equipment and labor skills are shared among RCCs. A part begins processing only when the required equipment and labor skill are both available; otherwise, it is looped back to check for the same resources after a two-minute delay. This delay avoids the supervisor selecting the same high priority part again and again when the required resources are not available. The reason for checking both equipment and labor skill at the same time is to avoid inefficient usage on either resource. Scenarios like seizing equipment and waiting for a labor skill, or seizing a labor skill and waiting for equipment would not happen under this logic.

Parts are sent to the next RCC defined in its specified sequence after finishing the current operation, and are sent back to the front shop when their repair sequences defined in WCD (Appendix A-1) are finished. Using Part #14 as an example (Table 4), there are five operations defined in the WCD, and the first operation is processed at the MEPCA RCC, equipment and the labor skill codes required are C01 and AC respectively. Subsequent RCCs and associated equipment and labor skill codes required are: MEPCB with G01 and AI, MEPCN with I05 and BI, MEPMW with I07 and BI, and MEPMW with I07 and BB. After all the specified operations are done, the part is routed back to the front shop. The *Sequence* data module of the Arena Advanced Transfer panel is used to model the repair sequences defined in the WCD for each part. The numbers of operations defined in each sequence are shown in Table 5.

Table 4. The Repairing Sequence of Part #14

Step	RCC	EC	SC	RCC Description
1	MEPCA	C01	AC	CHEM CLEAN ENG COMP
2	MEPCB	G01	AI	INSP/WCD/DECOS ENG C
3	MEPCN	I05	BI	X-RAY/TCR NDI/ECII
4	MEPMW	I07	BI	L/S-H/S COMPRESSOR
5	MEPMW	I07	BB	L/S-H/S COMPRESSOR

(WCD 60612R)

Table 5. Number of Operations Defined in Each Repairing Sequence

Sequence	Nomenclature	WCD	Number of Operations
1	DISK, STG 1 LPT	60663R	13
2	SEAL ROTATING	60635R	25
3	#2 DISK	60667R	16
4	MATING RING	60636R	13
5	#1 BLADE	60659R	4
6	SEAL, FRT LPT AIR	60662R	43
7	SHAFT LPTR	60674R	8
8	SPCR, LOWER SEAL	60665R	8
9	RETAINER, LPT #2	60669R	9
10	SUPORT, LPT CONE	60666R	7
11	RETAINER, LPT #1	60661R	9
12	#4 SEAL HSG-LPT	60637R	21
13	#2 BLADE	60668R	4
14	NUT #1	60612R	5
15	VENT, CENTER	60675R	4
16	NUT #2	60677R	4
17	SEPARATOR	60673R	5
18	SLEEVE, LPTR DAMPER	60660R	3

Selection of the Response Variable

According to the problem statement, there are two main response variables, the LPT rotor repair cycle time and WIP investment. The cycle time is used as an effectiveness metric, and the WIP investment is used as an efficiency metric. There is always a tradeoff between effectiveness and efficiency. Higher spare levels can always support a better cycle time; however, the WIP investment could be skyrocketed. One way to manage the tradeoff between two contradicting objectives is by applying Multiple Objective Linear Programming (MOLP). The generated Pareto optimal solution using

this approach assures that no other feasible solution allows an increase in one objective without decreasing the other objective (Ragsdale, 2001: 321). In short, two objectives are equally optimized.

Repair Cycle Time. Table 6 indicates that the current total component flow standard of LPT rotor is 28.28 days, which is the sum of disassembly and assembly time (7.15 days) and long flow part time (21.13 days for Part #6—Seal, FRT LPT AIR). One effective way to reduce the rotor repair cycle time is applying spares on those long flow parts, such as Part #1, #2, #3, #6, and #12. For instance, if a spare of Part #6 is applied, the long flow part time would become 14.14 days (Part #1), and the repair cycle could thus be reduced. Arbitrarily increasing the spare levels does not always reduce the repair cycle time effectively; RSM will thus be applied to estimate the optimal spare levels to support the minimal rotor repair cycle for each queuing policy.

WIP Investment. Each individual part of the LPT rotor associates with an investment value. In this study, following formula is applied to calculate the average WIP investment:

$$\textit{WIP investment} = \textit{Spare Cost} + \textit{In System Rotor Cost} \quad (6)$$

The *WIP investment* is a time-weighted value, where the *Spare Cost* is a fixed cost, the total cost of all spares applied, and the *In System Rotor Cost* is a variable cost, which only changes when an entire rotor enters or leaves the system. Too few spares would not effectively reduce the rotor repair cycle time or the number of rotors in the system on average, and thus may not decrease the *WIP investment*. Too many spares can increase the WIP investment directly through the spare cost. RSM will be applied to estimate the optimal spare levels to support minimal WIP investment for each queuing policy. The costs associated with each major part of the LPT rotor are shown in Table 7. The total

rotor cost, $117,412.00, is the sum of the total part cost, $56,317.53, and the associated overhead cost, $61,094.47. The WIP investment is incremented by the value of total rotor cost when a rotor enters the system, and decremented by the same value when a rotor leaves the system.

Table 6. LPT Rotor Standard Repair Cycle Time

CONTROL NUMBER		64212A
COMPONENT DESCRIPTION		F101 LPT ROTOR
COMPONENT END ITEM STOCK NUMBER		2840014168818JF
Part ID #	**Nomenclature**	**PART FLOWTIME (Days)**
1	DISK, STG 1 LPT	14.14
2	SEAL ROTATING	10.41
3	#2 DISK	12.07
4	MATING RING	5.55
5	#1 BLADE	4.97
6	SEAL, FRT LPT AIR	21.13
7	SHAFT LPTR	3.98
8	SPCR, LOWER SEAL	3.91
9	RETAINER, LPT #2	4.27
10	SUPORT, LPT CONE	3.69
11	RETAINER, LPT #1	4.24
12	#4 SEAL HSG-LPT	11.87
13	#2 BLADE	2.95
14	NUT #1	2.01
15	VENT, CENTER	2.41
16	NUT #2	1.49
17	SEPARATOR	2.04
18	SLEEVE, LPTR DAMPER	1.44
DISASSEMBLY AND		7.15
LONG FLOW PART TIME		21.13
TOTAL COMPONENT FLOW		28.28

(Adapted from Engine Component Flow Diagram, AFMCI 21-105, Chapter 4)

Table 7. LPT Rotor Costs

Part ID #	Nomenclature	Consumable & DLR Standard Price
1	DISK, STG 1 LPT	$16,585.02
2	SEAL ROTATING	$1,167.56
3	#2 DISK	$2,687.60
4	MATING RING	$1,468.73
5	#1 BLADE	$633.72
6	SEAL, FRT LPT AIR	$2,996.38
7	SHAFT LPTR	$8,959.21
8	SPCR, LOWER SEAL	$3,039.43
9	RETAINER, LPT #2	$4,688.74
10	SUPORT, LPT CONE	$5,563.42
11	RETAINER, LPT #1	$5,124.19
12	#4 SEAL HSG-LPT	$1,649.04
13	#2 BLADE	$420.44
14	NUT #1	$15.89
15	VENT, CENTER	$353.63
16	NUT #2	$2.52
17	SEPARATOR	$843.70
18	SLEEVE, LPTR DAMPER	$118.31
	Part Cost	$56,317.53
	Other Cost	$61,094.47
	Total Cost	**$117,412.00**

(Adapted from Tinker APS Demo Components)

Choice of Factors and Levels

Two types of factors being considered are queuing policies and spare levels:

Queuing Policies. Three different queuing policies being tested are First In First Out (FIFO), Shortest Process Time First (SPTF), and Lowest Arrival Index Value First (LAIVF).

First in first out (FIFO): The part arriving first in the queue is processed first. This policy is assumed to be the current queuing policy and our initial model will be built using this policy.

Shortest processing time first (SPTF): The part with the shortest process time in the queue is processed first. This policy might reduce the average process time of all the parts; however, the overall LPT rotor repair cycle might not be effectively reduced due to some parts with a long processing time might wait in a queue for a long time. The rotor assembly process could be delayed by waiting on one of any particular part. However, with spares of the long flow parts available, this policy could be a good one to apply.

Lowest rotor arrival index value first (LAIVF): For applying this queuing policy, once a rotor is disassembled, each of its parts is assigned an arrival index. This index is incremented with each rotor arrival. At the RCCs, a part with the lowest rotor arrival index gets processed first. This policy provides a higher priority in the back shop to complete a part of each type before repairing a subsequent part of the same type. Because of the stochastic nature of the repair times for each individual part and the complicated sequences they follow, the first set of parts to be processed with this policy will most likely not be the original set of parts from an incoming rotor. The overall rotor repair cycle might be reduced because a set of parts, instead of any particular type of part, is assigned with a higher priority to get through the back shop. As already mentioned in the *Model Construction* section, this index is different from the assemble-sequential index used at the assembly station.

Spare Levels. Table 8 illustrates the flow times and costs of five critical parts. They are considered critical because of their long flow times. The majority of delays during assembly are due to awaiting parts. This typically occurs when those critical parts are unavailable but required by the front shop for assembly. By applying an appropriate spare level on those critical parts, the average rotor repair cycle time can be

effectively reduced. Table 9 shows the region of interest defined by the spare levels. According to the historical LPT rotor arrival data (Appendix C), the LPT rotor arrival mean is 3.96 days. The center spare level of each critical part is based on this arrival mean and its average flow time. Using Part #1 as an example, its average flow time is 14.14 days, so the average number of rotor arrivals during its average flow time would be 3.6. Generally speaking, an average means only 50% of possibility. Thus, for avoiding less than 50% of possibility on spare stock out, the center spare levels of each part were set a little higher than the average rotor arrivals during their respective average flow time. There is no certain technique for defining the region of interest; however, a good guess on the region of interest surely could save a great amount of time. Considering both the variation in rotor arrivals and that the response surface may not be accurately estimated if the region of interest were too broad, the lower and higher spare levels of each critical part were set at minus or plus 3 of their center spare level.

Table 8. Critical Part Flow Times and Costs

Part ID #	Nomenclature	PART FLOWTIME	Consumable & DLR Standard Price
1	DISK, STG 1 LPT	14.14	$16,585.02
2	SEAL ROTATING	10.41	$1,167.56
3	#2 DISK	12.07	$2,687.60
6	SEAL, FRT LPT AIR	21.13	$2,996.38
12	#4 SEAL HSG-LPT	11.87	$1,649.04

Table 9. Spare Level Region of Interest

Part ID #	Average Flow Time	Average Rotor Arrival During Average Flow Time	Low	Center	High
1	14.14	3.6	2	5	8
2	10.41	2.6	1	4	7
3	12.07	3.1	1	4	7
6	21.13	5.4	3	6	9
12	11.87	3.0	1	4	7

Model Verification and Validation

Techniques proposed by Law and Kelton were applied to conduct the general model validation and verification (Law and Kelton, 2000: 269). For model verification, this model was first built and debugged in sub-models. The primary sub-models are disassembly, RCCs, and assembly stations. Each sub-model was tested individually, so the debugging process was conducted efficiently. After a sub-model was written, its logic was reviewed by the advisor and sponsors. In order to observe the logic flow more clearly, animation was applied. Simulated LPT rotor arrival times were compared with the historical data and the results suggested that values were being correctly generated.

In order to have an analysis that would make any sense at all, it is critical to have a valid model as the platform of experiment. Model validation is especially critical for this study since there is no such system that is only dedicated to LPT rotor repair in the real world. The only way to model the system for LPT rotor repair is through abstraction. What is not known has to be derived from what is known. At this point, the LPT rotor repair logic flow, standard flow times of LPT rotor and each individual part, and the repair sequence of each individual part are known. The process time of each repair sequence of each individual part, and the proper resource levels of equipment and labor skills are not known. It has also been identified that about 70% of the cycle times are non-value-added, such as queuing time. The following steps were conducted to build the model with similar characteristics as the system that is only dedicated to the LPT rotor repair.

First the rotor arrival distribution was defined by analyzing the historical LPT rotor arrival data (Appendix C). Figure 10 shows the histogram of the times between

rotor arrivals. By applying Arena Input Analyzer, the best distribution found and the data summary are shown in Table 10. There are 53 data points, and the mean time between LPT rotor arrivals is 3.94 days. Next, for finding the adequate resource levels and process times of each type of part at each RCC, it was first assumed that 80% of the cycle time of each individual part was non-value-added, so only 20% of the cycle time of each individual part was used for its total process time. Then, it was assumed that the total process time of a part is evenly distributed among those operations it goes through with some random variations (Table 11).

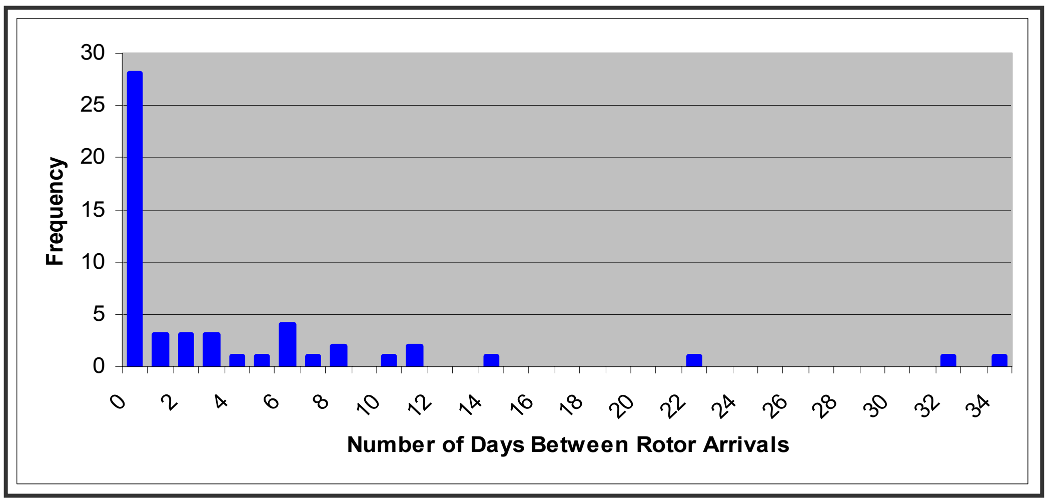


Figure 10. Times Between LPT Rotor Arrivals

In order to introduce queuing into the model, resources have to be limited. The model was first run with unlimited resources (equipment and labor skills). The maximum number used of each resource was then applied as a reference for limiting that particular resource. By proportionally reducing each labor skill level, the queuing caused by limited labor skill was introduced. Table 12 shows the description, maximum number used over 30 replications, and the implemented levels of the labor skill. Then, by proportionally reducing each equipment level, the queuing caused by limited equipment

was also introduced. Table 13 shows the description, maximum number used over 30 replications, and the implemented levels of the equipment.

Table 10. Fitted Distribution and Data Summary

Distribution	Beta	**Number of Data Points**	53
Expression	-0.5 + 35 * BETA (0.195, 1.34)	**Sample Mean**	3.94
Square Error	0.010692	**Sample Std Dev**	7.32

Table 11. Initial Applied Process Times

Part ID #	Cycle (day)	Cycle (Hour)	# Operations	Cycle / Op (Hour)	20% (Hour)
1	14.14	339.36	13	26.10	5.2
2	10.41	249.84	25	9.99	2.0
3	12.07	289.68	16	18.11	3.6
4	5.55	133.2	13	10.25	2.0
5	4.97	119.28	4	29.82	6.0
6	21.13	507.12	43	11.79	2.4
7	3.98	95.52	8	11.94	2.4
8	3.19	76.56	8	9.57	1.9
9	4.27	102.48	9	11.39	2.3
10	3.69	88.56	7	12.65	2.5
11	4.24	101.76	9	11.31	2.3
12	11.87	284.88	21	13.57	2.7
13	2.95	70.8	4	17.70	3.5
14	2.01	48.24	5	9.65	1.9
15	2.41	57.84	4	14.46	2.9
16	1.49	35.76	4	8.94	1.8
17	2.04	48.96	5	9.79	2.0
18	1.44	34.56	3	11.52	2.3

Table 12. Skill Description and Levels Applied

Index	Skill Code	Skill Description	Max # Used	Adjusted Levels
1	A2	3707 METALIZING	4	1
2	AB	8840/8602/MECH/ENG	19	4
3	AC	3769/5423/7009/3727	56	8
4	AI	3705 NDI	48	8
5	AJ	3414/3431/3416/MACH	8	2
6	AK	3712 HEAT TREAT	6	1
7	AR	3711 PLATING	5	1
8	BB	8840/8602/MECH/ENG	13	2
9	BC	3769/5423/7009/3727	5	1
10	BI	3705 NDI	38	5
11	BJ	3414/3431/3416/MACH	5	1
12	BR	3711 PLATING	8	1
13	CI	3705/NDI/FPI/MPI	6	1
14	CR	3711 PLATING	5	1

Table 13. Equipment Description and Levels Applied

Index	Equip Code	EC Description	Max # Used	Adjusted Levels
1	A06	VACUUM HEAT TREAT	6	1
2	A09	BAKE < 500 DEG F	5	1
3	A14	FLUORIDE ION CLEANING	5	1
4	A16	FURNACE VACUUM BRAZE	5	1
5	C01	CHEMICAL CLEANING	43	10
6	C02	VIBRATORY MACHINES	0	1
7	C03	POWER FLUSH	5	1
8	C04	DEGREASING (VAPOR, FREON, PRESSURE SPRAY)	5	1
9	C05	STEAM CLEAN	9	1
10	C06	HOT WATER CLEAN	5	1
11	D03	PEDESTAL DRILL	5	1
12	E03	ELEC DISCHARGE MACH/SIDE&VER RAM LG TUBE	6	1
13	G01	GENERAL/ HANDWORK WORK BENCH	47	8
14	G04	TOOL AND CUTTER GRINDER	5	1
15	G17	ABRASIVE FLOW MACHINE	4	1
16	G19	ACID ETCH	5	1
17	G21	SPARK EROSION GRIND (MACHINE)	6	1
18	I03	FLUORS PENETRANT INSP GROUP IV, VI & VIA	19	2
19	I05	MAGNETIC PARTICAL INSPECTION	8	2
20	I06	DE-MAG	4	1
21	I07	VIS/DIM INSPECT/WORK BENCH/HARNESS CHECK	36	4
22	I08	COORD MEASURING EQUIP (3 AXIS)	16	2
23	I11	RUNOUT TABLES/ROTARY	4	1
24	I15	COORD MEASUREMENT MACHINE	10	1
25	I16	ECII OR RFC MACHINES	9	1
26	I22	VIDEO MICRO INSP FOR HONEYCOMB/BORAZON	6	1
27	L01	ENGINE LATHE UP TO 18" / 30 CC	5	1
28	L04	VERTICAL TURRENT LATHE UP TO 42"	5	1
29	P01	CHROME PLATE	5	1
30	P02	NICKEL PLATE	5	1
31	P12	STRIPPING	8	1
32	Q02		6	1
33	T03	PLASMA SPRAY PROCESS	5	1
34	U01	DRY BLAST CABINET	4	1
35	U06	CO2 BLAST	4	1
36	U07	WATER BLAST	5	1
37	U10	RICE HULL BLAST	8	1
38	W07	SPOT WELD	5	1
39	W14	BRAZE ALLOY APPLICATION (TAPE & PASTE)	5	1

The effect of resource level on the flow part time is not linear. That is, by reducing one more particular resource, a significant queue might be introduced. Also the queuing time of those individual parts are quite dependent. Appendices A-4, A-5 and A-

6 show that many RCCs, equipment and labor skills are shared among different parts. Resource levels shown in Table 12 and 13 are thus considered appropriate for this working model. After the resource levels were decided, process times became the only adjustment knobs for matching the part flow times. Adjusting the process times is a recursive process confined by the available knowledge. Before finding the appropriate warm-up period, we could only use the best process times we have; that is, the process times that match the standard flow times. After the appropriate warm-up period is found, the data is examined from a different simulation time period. The process times will be adjusted again to match the standard flow times. Readjusting the process times is critical for getting more accurate analysis.

The standard flow times are the long-run outputs of the system, so those collected values should be from the steady-state of the simulation model. The initialization bias caused by using artificial and unrealistic initial conditions first has to be reduced. One method to reduce the impact of initial conditions is to divide each simulation run into two phases: first an initial phase from time 0 to time T_0, warm-up period, followed by a data collection phase from time T_0 to the stopping time $T_0 + T_E$ (run length). There is no widely accepted and proven technique to determine how much data to delete to reduce initialization bias to a negligible level. Plots can, at times, be misleading, but they are still recommended (Banks and others, 1999: 456). Based on 5 replication runs, 90 days was decided as the warm-up period of the working model by taking both response variables into account (Figure 11).

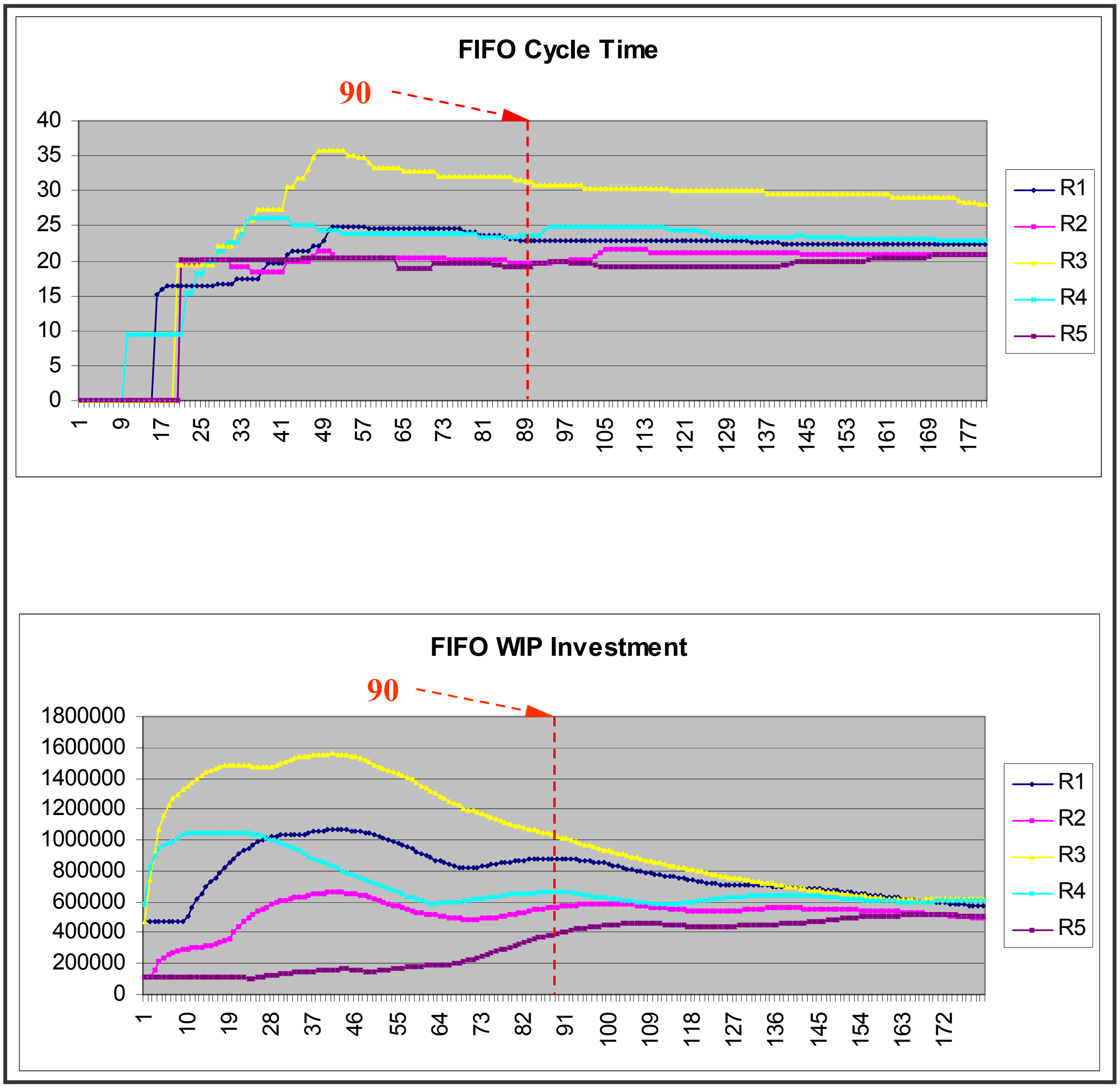


Figure 11. Deciding The Warm-up Period

By applying a warm-up period, the initialization bias in the point estimator was reduced to a negligible level. The method of independent replications then was used to estimate point-estimator variability and to construct a confidence interval. In general, the larger the sample size, the smaller the standard error of the point estimator. The larger sample size can be due to a longer run length per replication, or to more replications

(Banks and others, 1999: 461). The run length was already selected as six months. In order to find the appropriate number of replications with an acceptable confidence interval half width, 10 independent replications were used to obtain an initial estimate S_0^2 of the population variance σ^2. To meet the desired half width (h.w.) criterion, a sample size R must be chosen such that $R \geq R_0$ and

$$h.w. = \frac{t_{\alpha/2,R-1} S_0}{\sqrt{R}} \leq \varepsilon \quad (7)$$

where ε is the specified h.w. error criterion. By applying Equation 7 with the S_0 found, Table 14 shows the candidate number of replications with the respective estimated half widths. The number of replications was decided as 25 because there would not be much value to run more replications. Table 15 summaries the implemented process times, the standard flow times, and the generated flow times. The generated rotor cycle time would be shorter than its standard cycle time because 22% of Part #6 assumed replaced or serviceable (see Table 2) was not included in the calculation of mean repair flow time. By counting those 22% of non-repairing Part #6, the overall average flow time of Part #6 as well as the rotor cycle time would be shortened.

Table 14. Number of Replications and Estimated Half Width (95% CI)

Reps	10	15	20	25	30	35	40
Cycle Time	1.29	1.05	0.91	0.82	0.74	0.69	0.65
WIP Investment	139,459	113,868	98,613	88,202	80,517	74,544	69,730
Note	$t_{\alpha/2,9}$ = 2.26, S_0*(Cycle Time)* = 1.8052, S_0*(WIP Investment)* = 195,137						

Choice of Experimental Design

In order to find the Pareto optimal solution, the response surfaces of both the rotor cycle time and WIP investment have to be estimated for each queuing policy. Let there be three candidate systems which applying FIFO, SPTF, LAIVF as their respective queuing policy. For each system, RSM will be applied to estimate the effect provided by different spare levels within the region of interest illustrated in Table 9. The estimated response surfaces will be implemented into the Linear Programming (LP) optimization spreadsheet separately. The individually optimized objective values will then be used as the target values in the MOLP optimization spreadsheet. By assigning equal weights on both target values, the Pareto optimized solution will be suggested. That is the spare levels suggested equally optimize both the rotor cycle time and the WIP investment. The Pareto optimizing spare levels will then be implemented to each simulation system model. The results of 25 replications will be used to compare the performances of these three different systems. These results will be presented in Chapter IV.

Summary

In this chapter, the problem statement was first briefly revisited and scoped down. Queuing policy and spare implementation were focused as the APS analysis for this study. The response variables –rotor repair cycle time and rotor repair WIP investment were also recognized as the metrics of effectiveness and efficiency. Two main factors are queuing policy and spare level. The model was quite successfully abstracted according to the results shown in Table 15. A good amount of effort was put in the model validation process. The working model is considered as a valid experiment platform for the

following analysis. Chapter IV will conduct the experiments described in the Choice of Experimental Design section above, and focus on finding the best mix of queuing policy and spare levels to support Pareto optimal rotor repair cycle and WIP investment.

Table 15. Process Times Applied And Cycle Times Generated

Part ID #	Nomenclature	Adjusted Mean Process Time	Standard Flow Time	Generated Flow Time (Repaired Items)
1	DISK, STG 1 LPT	15.2	14.14	13.59
2	SEAL ROTATING	4	10.41	9.90
3	#2 DISK	10.2	12.07	11.68
4	MATING RING	1.9	5.55	5.67
5	#1 BLADE	100% Replaced		
6	SEAL, FRT LPT AIR	6.4	21.13	20.67
7	SHAFT LPTR	2.7	3.98	4.16
8	SPCR, LOWER SEAL	2.7	3.91	3.93
9	RETAINER, LPT #2	1.4	4.27	4.89
10	SUPORT, LPT CONE	2	3.69	3.97
11	RETAINER, LPT #1	100% Replaced		
12	#4 SEAL HSG-LPT	8	11.87	11.70
13	#2 BLADE	100% Replaced		
14	NUT #1	3	2.01	1.98
15	VENT, CENTER	4.8	2.41	2.46
16	NUT #2	2	1.49	1.56
17	SEPARATOR	1.5	2.04	2.28
18	SLEEVE, LPTR DAMPER	0.5	1.44	2.13

(Number of Replications: 25, Warm-up Period: 90 days, Run Length: 80 days)

IV. Results

Introduction

In this chapter, we present results of our experiment and our output analysis. The experiment steps described in Chapter III will be followed throughout this chapter. For each queuing policy, the response surfaces of rotor cycle time and WIP investment within the region of interest will first be estimated. The estimated response surfaces will then be applied to the respective rotor repair cycle and WIP investment Linear Programming (LP) optimization spreadsheets. Those two independently optimized objectives will be applied to the MOLP spreadsheet as the objective targets values. Next, both targets will be assigned with an equal weight, and the Pareto optimal spare levels generated by the MOLP spreadsheet will be applied to the simulation model. Finally, the results generated by 25 replication runs from each queuing system will be used to identify the best mix of queuing policy and spare levels for LPT rotor repair.

Response Surface Methodology

Screening Experiment

By choosing the FIFO system as a representative model, a screening experiment was conducted to find the significant factors. A 2^{5-2}_{III} fractional factorial design was used for screening the main effects provided by those five candidate factors. Table 16 shows the screening design and results over 10 replications at each design point for both the rotor repair cycle time and the WIP investment. Eight experiment runs provide seven degrees of freedom. Five degrees of freedom are used to estimate the five main effects,

and two degrees of freedom are left unexplained. Those estimated effects and p-values shown in Table 17 and Table 18 provide a good amount of information for the significances of those factors. Factors with smaller p-values provide more effect on the response. For the cycle time response variable, the most statistically significant factor is Part #6, while Part #2, Part #3, and Part #12 also provide some practically significant effect. For the WIP investment response variable, both Part #1 and Part #6 provide statistically significant effect, while Part #2 and Part # 12 provide some practically significant effect. These results agree with the facts that Part #6 has the longest flow time and Part #1 is the most expensive part. Part #1 and Part #6 were thus selected as the main factors for defining the response surfaces of both response variables. Since Part #2, Part #3, and Part#12 have some practically negative effect on both response variables, their spare levels were set a little higher than their center levels for reducing the response means. This rationale of defining the region of interest would also be true for the other two queuing policies, so the region of interest shown in Table 19 is applied to the other two systems as well.

Table 16. Screening Design and Results (FIFO)

Run	**P #1**	**P #2**	**P #3**	**P #6**	**P #12**	**Cycle**	**WIP**
1	2	1	1	3	7	17.6291	465809
2	2	1	7	9	1	15.7841	433601
3	2	7	1	9	1	16.1385	436238
4	2	7	7	3	7	16.4002	447070
5	8	1	1	9	7	15.3926	505718
6	8	1	7	3	1	18.2493	563983
7	8	7	1	3	1	17.9975	552477
8	8	7	7	9	7	11.9051	444683

Table 17. Effect Analysis / Cycle Time

Factor	P #1	P #2	P #3	P #6	P #12
Effect	-0.60185	-1.15345	-1.20475	-2.76395	-1.7106
P-value	0.411481	0.187236	0.175489	0.041946	0.099653

Table 18. Effect Analysis / WIP Investment

Factor	P #1	P #2	P #3	P #6	P #12
Effect	71035.75	-22160.75	-17726.25	-52274.75	-30754.75
P-value	0.02376067	0.18520093	0.252822746	0.042604899	0.110136553

Table 19. Redefined Region of Interest

Part ID #	Low	Center	High
1	2	5	8
6	3	6	9
Note	Spare levels of Part #2, Part #3, and Part #12 are set at 5.		

Estimation of Response Surfaces

Central composite design (CCD) was applied for estimating the response surfaces of the cycle time and the WIP investment. CCD is recognized as the most popular response surface design. It combines a two-level fractional factorial, center points, and axial points. For center points, all factor values are set at their midrange values. For axial points, all but one factor are set at midrange values and one factor is set at outer (axial) value. Due to the reason that we would like to avoid outer values (they might not be feasible for this study), the axial points were set on the face (-1 or 1). The price of this approach is the higher uncertainty of prediction near the axial points, which does not provide significant effect on this study.

The CCD results of each system are shown in Table 20, Table 21, and Table 22.The corresponding estimated response surface functions are shown as tabular form in Table 23, Table 24, and Table 25. The *R Square* values shown suggest these estimated

functions are quite satisfactory. These estimated functions were next applied to the Linear Programming Optimization section for finding the Pareto optimal response variables.

Table 20. Central Composite Design and Results / FIFO

Run	P1	P6	Cycle	WIP
1	2	3	16.7474	446920
2	2	9	14.1923	405776
3	8	3	15.7364	513664
4	8	9	12.4371	444909
5	2	6	14.2495	395249
6	8	6	13.1396	456108
7	5	3	15.9878	469439
8	5	9	12.6229	403860
9	5	6	12.9489	401639
10	5	6	12.9489	401639

Table 21. Central Composite Design and Results / SPTF

Run	P1	P6	Cycle	WIP
1	2	3	16.1678	435607
2	2	9	14.4271	407874
3	8	3	15.9081	514340
4	8	9	12.4626	446212
5	2	6	15.0519	414874
6	8	6	13.5002	466702
7	5	3	16.0059	474927
8	5	9	12.4341	400856
9	5	6	13.2901	416773
10	5	6	13.2901	416773

Table 22. Central Composite Design and Results / LAIVF

Run	P1	P6	Cycle	WIP
1	2	3	15.8374	425128
2	2	9	13.5858	385624
3	8	3	15.3795	504510
4	8	9	12.4576	449474
5	2	6	13.8681	385737
6	8	6	12.7948	448999
7	5	3	14.9447	446376
8	5	9	12.6396	404140
9	5	6	12.9848	406249
10	5	6	12.9848	406249

Table 23. Estimated Response Surface Functions / FIFO

Term	Coefficient	P_1	P_6	P_1P_6	P_1^2	P_6^2	R^2
Cycle Time	13.026814	-0.646017	-1.53655	-0.18605	0.5898214	1.2006214	0.99398
WIP Investment	403888.07	27789.333	-29246.33	-6902.75	19541.357	30512.357	0.993129

Table 24. Estimated Response Surface Functions / SPTF

Term	Coefficient	P_1	P_6	P_1P_6	P_1^2	P_6^2	R^2
Cycle Time	13.422829	-0.629317	-1.459667	-0.4262	0.7204929	0.6644429	0.973429
WIP Investment	419886.79	28149.833	-28322	-10098.75	17787.429	14890.929	0.973651

Table 25. Estimated Response Surface Functions / LAIVF

Term	Coefficient	P_1	P_6	P_1P_6	P_1^2	P_6^2	R^2
Cycle Time	12.934436	-0.443233	-1.246433	-0.167575	0.4473786	0.9080786	0.994774
WIP Investment	404875.57	34415.667	-22796	-3883	13865.857	21755.857	0.996309

Linear Programming Optimization

The response surface functions estimated above were applied to the following LP optimization spreadsheets. The response surface functions are defined by the coded forms of the significant factors, so the natural variables have to be transformed to coded forms (between –1 and 1) by using the following equation:

$$x = \frac{\xi - [high(\xi) + low(\xi)]/2}{[high(\xi) - low(\xi)]/2} \qquad (8)$$

where x is coded value and ξ is natural variable. Table 26 illustrates the corresponding coded values for the spare levels within the region of interest.

Table 26. Corresponding Coded Values Within The Region Of Interest

Natural	2	3	4	5	6	7	8	9
P #1	-1	-0.67	-0.33	0	0.33	0.67	1	
P #6		-1	-0.67	-0.33	0	0.33	0.67	1

In both of the cycle time and WIP investment LP optimization spreadsheets the decision variables are the spare levels of Part #1 and Part #6. They are constrained to the lower and upper bounds defined in the focusing region. The coded variables are converted with Equation 8. The objective cells, cycle time or WIP investment, are calculated with the estimated equation shown above. Next, these individually optimized objectives are used as the target values in the MOLP spreadsheets. There, the *MINIMAX* objectives are applied to find the Pareto optimal solutions (Ragsdale, 2001: 317). The MOLP spreadsheet is not much different from the LP spreadsheet introduced above, only the MINIMAX objective cell is also a changing cell, and the weighted percent deviations of both objectives have to be less than the MINIMAX objective. By minimizing the maximal weighted percent deviation, the Pareto optimal cycle time and WIP investment values are generated. The LP optimization spreadsheets are shown in Appendix C. For each system, the optimized responses and corresponding spare levels are shown in Table 27, Table 28, and Table 29.

Table 27. FIFO / Optimized Responses and Corresponding Spare Levels

Response Variables	P1	P6	Mean
Cycle Time	7	8	12.29
WIP Investment	3	7	389,222
Cycle Time & WIP Investment	5	8	12.54 397,952

Table 28. SPTF / Optimized Responses and Corresponding Spare Levels

Response Variables	P1	P6	Mean
Cycle Time	7	9	12.24
WIP Investment	3	8	401,251
Cycle Time & WIP Investment	5	9	12.63
			406,456

Table 29. LAIVF / Optimized Responses and Corresponding Spare Levels

Response Variables	P1	P6	Mean
Cycle Time	7	8	12.34
WIP Investment	2	7	380,439
Cycle Time & WIP Investment	4	8	12.74
			390,279

System Performance

In general, higher levels of spares can support a shorter LPT rotor cycle time. In order to find the spare levels that are cost efficient, the WIP investment is applied as a trade-off measuring metric. The WIP investment metric plays a critical role of finding reasonable spare levels that are both effective in the sense of maintenance and efficient in the sense of cost. Analyzing the results shown in Table 27, Table 28, and Table 29, the recommended spare levels for the critical parts are shown in Table 30.

Table 30. Recommended Spare Levels

	P #1	P #2	P #3	P #6	P #12
Spares	5	5	5	9	5

Part #1 is critical because the cost of Part #1 ($16,585.02) is about 5 to 8 times higher than the other four parts, and its average flow time is the second longest one (14.14 days). By considering both response variables, the three MOLP results suggest setting the spare level of Part #1 at 4 or 5. In the Screening Experiment section, the spare levels of Part #2, Part #3, and Part #12 were decided as 5. It is reasonable to set the Part #1's spare level as 5 since it has the second longest flow time. For Part #6, the three

MOLP results suggest setting its spare level at 8 or 9. Since its cost is lower ($2,996.38), and it has the longest flow time (21.13 days), it is reasonable to set its spare level at 9.

By applying the spare levels shown in Table 30, additional experiments were run. Using the results of 25 replication runs of each system, the performances of the three systems were compared. Together with the results of each system without applying spares, the cycle time results are shown in Table 31, and the WIP investment results are shown in Table 32. For easier observation, their corresponding average values and 95% confidence intervals are summarized in Table 33 and Table 34.

Table 31. Average Cycle Times

Replication	No Spares			With Spares		
	FIFO	SPTF	LAIVF	FIFO	SPTF	LAIVF
1	23.01	23.41	25.28	13.33	12.56	14.24
2	24.11	21.82	21.11	12.57	12.30	12.84
3	21.80	22.34	23.11	12.15	11.43	11.78
4	24.61	28.55	25.62	14.79	15.47	14.79
5	20.71	22.84	21.78	11.36	11.02	11.58
6	21.98	28.09	23.38	14.24	14.67	13.66
7	22.69	22.32	24.38	11.85	12.64	12.12
8	21.12	22.80	20.04	11.89	10.33	11.50
9	21.62	22.34	20.38	10.73	10.30	11.03
10	21.48	24.53	22.40	13.32	13.62	12.86
11	33.95	29.62	29.51	20.60	22.81	18.87
12	24.44	28.52	29.18	18.14	16.37	15.20
13	22.82	24.56	21.77	13.88	12.92	13.48
14	20.90	19.19	21.26	10.43	9.74	10.28
15	24.25	25.61	23.42	13.55	12.90	14.27
16	26.15	24.09	24.59	13.13	13.36	13.80
17	22.89	21.54	20.29	11.46	10.32	11.25
18	23.01	25.53	21.34	15.37	13.87	15.08
19	28.15	30.38	28.15	17.77	19.10	17.81
20	24.38	24.85	21.41	11.97	13.50	13.08
21	23.59	25.35	23.41	14.95	16.34	14.79
22	27.39	28.46	28.06	18.09	20.45	18.47
23	23.83	25.83	23.78	14.94	14.87	14.80
24	25.62	25.41	24.14	11.53	16.58	12.82
25	24.54	28.70	24.24	14.49	13.68	14.58
Mean	23.96	25.07	23.68	13.86	14.05	13.80

(25 Replications, Warm Up Time: 90 days, Simulation Length: 180 days)

Table 32. Time-weighted WIP Investment

Replication	No Spares			With Spares		
	FIFO	SPTF	LAIVF	FIFO	SPTF	LAIVF
1	517,040	529,406	574,714	378,962	360,889	392,628
2	670,007	611,677	576,809	427,885	425,387	436,962
3	405,321	414,810	426,621	343,997	331,636	335,912
4	839,744	978,628	873,194	600,480	614,450	605,375
5	472,138	528,988	501,218	350,783	333,458	353,712
6	683,215	887,432	733,027	532,355	545,133	512,327
7	482,479	475,856	521,177	369,164	368,642	372,969
8	324,491	354,326	309,263	287,854	276,785	280,979
9	422,906	437,879	396,885	300,528	301,139	318,064
10	581,238	657,362	607,530	446,590	451,035	432,473
11	1,436,409	1,262,392	1,257,654	940,343	1,033,342	877,618
12	823,355	947,322	963,473	697,249	638,996	609,837
13	493,741	538,270	469,799	389,700	355,023	382,367
14	345,419	317,481	352,923	302,249	290,548	301,890
15	615,064	641,234	592,854	430,011	423,132	447,451
16	630,861	592,125	599,268	437,641	430,064	457,571
17	466,974	437,830	410,904	332,863	311,314	327,099
18	648,714	670,539	584,085	504,125	504,736	509,884
19	982,632	1,061,439	992,004	703,742	733,274	684,933
20	483,876	486,886	428,512	339,107	347,091	337,247
21	602,547	652,039	597,479	475,511	503,434	479,526
22	912,985	948,662	935,210	692,940	762,320	703,876
23	629,308	677,724	625,127	472,816	464,968	471,521
24	459,129	454,232	437,306	332,425	375,417	349,039
25	543,581	627,294	543,960	413,875	383,502	392,252
Mean	618,927	647,673	612,440	460,128	462,629	454,940

(25 Replications, Warm Up Time: 90 days, Simulation Length: 180 days)

Table 33. Independent 95% CIs of Cycle Times

System	Without Spares		With Spares	
	Average	95% CI Half Width	Average	95% CI Half Width
FIFO	23.96	(22.79, 25.13) 1.17	13.86	(12.8, 14.92) 1.06
SPTF	25.07	(23.87, 26.27) 1.20	14.05	(12.72, 15.38) 1.33
LAIVF	23.68	(22.55, 24.81) 1.13	13.80	(12.88, 14.72) 0.92

Table 34. Independent 95% CIs of WIP Investment

System	Without Spares		With Spares	
	Average	95% CI Half Width	Average	95% CI Half Width
FIFO	618,927	(520247, 717607) 98,680	460,128	(394593, 525663) 65,535
SPTF	647,673	(548937, 746409) 98,736	462,629	(389061, 536197) 73,568
LAIVF	612,440	(517635, 707245) 94,805	454,940	(394985, 514895) 59,955

These confidence intervals above provide good information about individual system performances; however, they are not as reliable for comparing the system performances. In order to obtain more precise estimates of the mean difference, common random numbers (CRN) were already applied in the simulation model, so the same random numbers were used to simulate the alternative system designs. CRN, or correlated sampling, usually reduces the variance of the simulated difference of the performance measures and thus can provide, for a given sample size, more precise estimates of the mean difference than can independent sampling (Banks and others, 1999: 475). In following sections, the three queuing policies applying the recommended spare levels were first compared. Then, the potential improvements given by applying recommended spare levels were analyzed.

Comparing the Three Queuing Policies

FIFO is assumed to be the queuing policy applied by the current system. Comparing with FIFO, the other two alternative queuing policies would cost more to implement. Thus, the alternative queuing policy would not be worthwhile to implement unless there is enough evidence to show its system performance is significantly better than the FIFO system's. As mentioned above, the WIP investment was used primarily as

a cost monitoring metric for assuring a cost efficient spare level. Since the recommended spare levels were already decided, the cycle time would be used as the primary metric for comparing system performances.

The paired t test was used since CRN generators were implemented in the simulation model. The paired t test allows us to compare the group means, while taking the advantage of the information gained from the pairings. In general, if the responses are positively correlated, the paired t test gives a more significant p value than the grouped t test (Lehman, 2001:150). The Matched Pairs platform offered in *JMP* was applied to compare means between two response columns using a paired t test. For SPTF versus FIFO, the confidence interval shown in Table 35 suggests that the two means are not significantly different (0 is well covered by the 95% CI). For LAIVF versus FIFO, the confidence interval shown in Table 36 suggests that the two means are not significantly different either (0 is well covered by the 95% CI).

Table 35. Paired t Test Results of SPTF versus FIFO (Cycle Time)

SPTF	14.046	t-Ratio	0.60685
FIFO	13.8612	DF	24
Mean Difference	0.1848	Prob > |t|	0.5496
Std Error	0.30452	Prob > t	0.2748
Upper95%	0.8133	Prob < t	0.7252
Lower95%	-0.4437		
N	25		
Correlation	0.88664		

Table 36. Paired t Test Results of LAIVF versus FIFO (Cycle Time)

LAIVF	13.7992	t-Ratio	-0.35933
FIFO	13.8612	DF	24
Mean Difference	-0.062	Prob > |t|	0.7225
Std Error	0.17255	Prob > t	0.6388
Upper95%	0.29411	Prob < t	0.3612
Lower95%	-0.4181		
N	25		
Correlation	0.94601		

According to these paired t test results, we concluded that by applying the recommended spare levels, neither of the alternative queuing policies is significantly better than FIFO. Thus, it would not be worthwhile to implement either of the more sophisticated queuing policies.

Comparing Systems With or Without Applying Spares

After finding that FIFO would be a good queuing policy to use, we next analyzed the potential improvements that recommended spare levels could provide with the FIFO system. By summarizing Table 33 and Table 34, the mean differences on the cycle time and WIP investment for FIFO with spares versus without spares are shown in Table 37. The differences are clearly practically significant, though the paired t test is used to test whether the differences are statistically significant as well. For cycle time, the confidence interval shown in Table 38 suggests that the two means are significantly different (the 95% CI is well above 0). For the WIP investment, the confidence interval shown in Table 39 suggests that the two means are significantly different (the 95% CI is well above 0). The mean difference confidence intervals of both responses summarized in Table 40 suggest that by applying the recommended spare levels on the FIFO system, both the LPT rotor repair cycle time and WIP investment could be significantly reduced.

Table 37. Mean Response Differences (With Spares versus Without Spares / FIFO)

Response	Cycle Time (days)	WIP Investment
Without Spares	23.96	$618,927
With Spares	13.86	$460,128
Mean Difference	10.10	$158,799

Table 38. Paired t Test Summary of Cycle Times

Cycle NS	23.9616	t-Ratio	27.13699
Cycle S	13.8612	DF	24
Mean Difference	10.1004	Prob > |t|	<.0001
Std Error	0.3722	Prob > t	<.0001
Upper95%	10.8686	Prob < t	1.0000
Lower95%	9.33222		
N	25		
Correlation	0.76684		

Table 39. Paired t Test Summary of WIP Investments

WIP NS	618927	t-Ratio	8.722956
WIP S	460128	DF	24
Mean Difference	158799	Prob > |t|	<.0001
Std Error	18204.7	Prob > t	<.0001
Upper95%	196372	Prob < t	1.0000
Lower95%	121227		
N	25		
Correlation	0.97578		

Table 40. Potential Improvements (FIFO With Recommended Spare Levels)

Performance Metric	Potential Improvement (95% CI)
Cycle Time	9.33 ~ 10.87 days
WIP Investment	\$121,227 ~ \$196,372

Summary

Using FIFO as a representative model, the screening experiment first identified Part #1 and Part #6 as the most significant factors among those five critical parts for both of the response variables. The region of interest was redefined based on the effects estimated in the screening experiment. Since the rationale for defining the region of interest would also be true for the other two queuing policies, the redefined region of interest was also applied to the alternative systems. For each system, the response surfaces of cycle time and WIP investment were estimated. The R^2 values suggest those

estimated functions are quite adequate. Applying those estimated functions to the MOLP optimization spreadsheets, the Pareto optimal cycle times and WIP investments alone with the corresponding spare levels were found for each system.

For obtaining more precise estimation on the response variables, 25 replication runs were conducted for each system. The corresponding confidence intervals show that there is not significant difference among the three queuing systems applying the recommended spare levels. However, the differences between a given queuing system with or without applying spares are quite significant. The more precise comparison among the three systems applying recommended spare levels was conducted first. Since CRN were applied in the simulation model, the paired t test was used. Setting FIFO as the current queuing policy, the results suggest neither of the alternative policies, SPTF or LAIVF, is significantly better than FIFO. Thus, we concluded that it would not be necessary to implement either of the more sophisticated queuing policies.

Next, the potential improvements on the FIFO system given by applying the recommended spare levels were estimated. Table 40 shows the mean cycle time could be reduced by 9.3 to 10.9 days (95%CI), and the time-weighted WIP investment could be reduced by \$121K to \$196K (95% CI).

The overall conclusion of the experiment is that different queuing policies do not provide significant difference on the LPT rotor repair. However, applying the recommended levels of spares could reduce the rotor cycle time and associated WIP investment effectively and efficiently.

V. Conclusion

Introduction

With the theoretical foundation laid in Chapter II, Chapters III and IV applied M&S, RSM, and LP to reduce the LPT rotor cycle time and WIP investment as a means to reduce the F101 engine depot maintenance cycle time. Experiments were conducted in order to answer the research questions identified in Chapter I. This chapter now ties the findings of previous chapters together to answer the research questions. These questions are individually addressed below. Following the discussion of the research questions, additional findings are discussed. Finally, recommendations for future research are presented.

Conclusions

Each of the four research questions from Chapter I is now restated and discussed based on the information contained in Chapters II through IV.

1. *What type of problem-solving model is most appropriate for conducting this research study?*

As evidenced from the literature, the primary tool used in this type of research is M&S. Due to the nature and complexity of the problem, simulation has been determined to be superior to other tools. Simulation alone, however, provides merely the best answer of the solutions tried and is thus limited in it ability to find the "best" answer. This research, thus, choose an approach that combines both simulation and optimization techniques.

2. *Is the current system only dedicated to LPT rotor repair? If not, how to build a model that adequately represent the LPT rotor repair process?*

Based on the information obtained from personnel interviews, we found that there is no such system that is only dedicated to LPT rotor repair. Those concepts proposed by Law and Kelton, already mentioned in Chapter II, suggest that "a simulation model of a complex system can only be an approximation to the actual system, no matter how much effort is spent on model building, and a simulation model should always be developed for a particular set of purposes." In other words, for a complex system, model abstraction is always necessary to a certain level in building a simulation model. As a matter of fact, model abstraction is quite common since many times a version of the modeled system might not exist. For this study, the abstraction procedures were discussed in Chapter III Model Verification and Validation section.

3. *Does the abstracted model adequately represent the LPT rotor repair process?*

As proposed by Law and Kelton, "Conceptually, if a simulation model is "valid," then it can be used to make decisions about the system similar to those that would be made if it were feasible and cost-effective to experiment with the system itself." We would argue that the abstracted model adequately represents the LPT rotor repair process for three main reasons. First, the model framework is adequately built based on Figure 7 and those relevant WCDs. Second, as shown in Table 41, the generated part flow times are quite close to the standard part flow times. In fact there is less than a 5% difference for all parts except for a few with very short standard flow times. Third, the adjusted process times shown in Table 42 illustrate one important characteristic of the model. It is recognized that in general up to 80% of the flow times are contributed by non-value-

added time, such as queuing and awaiting parts. In this model, 40% to 90% of the flow times are contributed by the non-value-added times. Overall, this model not only generates historical outputs using historical inputs, it also adds an adequate amount of non-value-added time on those part flow times.

4. *Could use of APS reduce depot repair cycle time and WIP investment for the F101 LPT rotor?*

Queuing policy and spare application are the applications of APS considered in this study. Based upon the results, we found that neither SPTF nor LAIVF queuing policy is significantly better than FIFO. Spare application, however, does significantly reduce both the cycle time and WIP investment of the LPT rotor. By applying the recommended spare levels shown in Table 30 on the FIFO system, both the mean rotor cycle time and time-weighted WIP investment could be significantly improved (See Table 40). In other words, by investing about $137K on the recommended levels of spares (Table 43), the mean LPT rotor repair cycle time could be reduced by 9 to 10 days (more effective), and the overall time-weighted WIP investment could be lowered by $121K to $196K (more efficient). Since the rotor arrival rate might change in the future, the best spare levels may need to be modified based on the future usage of the spares.

Table 41. Standard Flow Times versus Generated Flow Times

Part ID #	Standard Flow Time	Generated Flow Time	Percentage Error (%)
1	14.14	13.59	-3.9%
2	10.41	9.90	-4.9%
3	12.07	11.68	-3.2%
4	5.55	5.67	2.2%
6	21.13	20.67	-2.2%
7	3.98	4.16	4.5%
8	3.91	3.93	23.2%
9	4.27	4.89	14.5%
10	3.69	3.97	7.6%
12	11.87	11.70	-1.4%
14	2.01	1.98	-1.5%
15	2.41	2.46	2.1%
16	1.49	1.56	4.7%
17	2.04	2.28	11.8%
18	1.44	2.13	47.9%

Table 42. Generated Non-Value-Added Time (hours) %

Part ID #	# Ops.	Applied Process Time / Op.	Total Process Time (A)	Standard Flow Time (B)	Percentage of Non-Value-added Time (1-(A/B))
1	13	15.2	197.6	339.36	41.8%
2	25	4	100	249.84	60.0%
3	16	10.2	163.2	289.68	43.7%
4	13	1.9	24.7	133.2	81.5%
6	43	6.4	275.2	507.12	45.7%
7	8	2.7	21.6	95.52	77.4%
8	8	2.7	21.6	76.56	71.8%
9	9	1.4	12.6	102.48	87.7%
10	7	2	14	88.56	84.2%
12	21	8	168	284.88	41.0%
14	5	3	15	48.24	68.9%
15	4	4.8	19.2	57.84	66.8%
16	4	2	8	35.76	77.6%
17	5	1.5	7.5	48.96	84.7%
18	3	0.5	1.5	34.56	95.7%

Table43. Recommended Spare Levels and Associated Cost

Part #	1	2	3	6	12
Spares	5	5	5	9	5
Cost / Unit	$16,585.02	$1,167.56	$2,687.60	$2,996.38	$1,649.04
Sub-total	$82,925.10	$5,837.80	$13,438.00	$26,967.42	$8,245.20
Total	$137,413.52				

Additional Findings

Model Abstraction

Model abstraction is critical for this study. Only the current LPT rotor repair process is adequately abstracted and further analysis could be conducted. For abstracting the working model, there was not much to modify on the logic flow, so the mean process times of each part at each RCC and the resource levels were the only primary adjustment knobs. Those knobs were tuned in three steps. First, the mean process time (value-added time) of each part was first set as 20% of its flow time. Then, the historical outputs were approximated by adjusting the resource levels with the historical inputs applied. The historical outputs could only be approximated to certain levels because part flow times are highly dependent (some parts go through same RCCs and share same resources). In the last step, after the adequate resource levels were found, the mean process times were adjusted again to match the outputs closer. Taking this approach, model abstraction was done quite efficiently and successfully. Not only were historical outputs matched with the historical inputs applied, but also an adequate amount of non-value-added times were generated.

RSM and MOLP Combined Approach

The RSM and MOLP combined approach applied is quite efficient for determining LPT rotor component spare levels. Additionally, this approach can be generalized to find the optimal spare levels for the other three F101 engine modules. In order to meet the ultimate goal of reducing the cycle time of the F101 engine, overall optimization is necessary; tradeoffs will have to be made among all four modules, low-pressure turbine, high-pressure turbine, high-pressure compressor, and fan.

In Chapter IV, a total of 38 experiment runs were conducted (8 Screening Experiment Runs + 3 Queuing Policies × (10 Central Composite Design Runs)) to estimate the response surfaces for each queuing policy. The possible combinations of queuing policies and spare levels of those critical parts are $3 \times 7^5 = 50421$. Obviously, the experimental design applied is a very efficient one. The tradeoff of RSM is between effectiveness and efficiency. More accurate response surfaces could be estimated by running more experiments. However, the core concept of RSM is to obtain an accurate enough estimation with as few experiment runs as possible. As shown in Table 23 through Table 25, the R^2 values suggest the estimated functions are quite adequate. In addition, the spare levels found by the MOLP optimization spreadsheets provide Pareto optimal responses.

Recommendations for Future Research

In the sense of scope, the higher-level goal above this study is reducing the cycle time of F101 engine depot maintenance. This working model could be expanded to include all four modules of F101 engine. Since the existing depot engine maintenance process is not only dedicated to the F101 engine, model abstraction is still going to play a critical role. In the sense of scale, significant details such as levels of bench stocks could be added into the model. The bench stocks and sub-components for repairing those parts are assumed to be sufficient in this study. This assumption may not be valid in some situations. In addition, information on actual resource levels and RCC process times could make more valid and precise analysis.

Summary

In this study, we found that by applying appropriate levels of spares on selected parts with long flow times, the repair cycle time and WIP investment for the F101 LPT rotor could be significantly reduced. This study establishes a valid and efficient approach for reducing repair cycle time and WIP investment for the LPT rotor. The simulation model could be expanded in sense of scope, so tradeoffs for the entire F101 engine repair could be analyzed globally. This study successfully illustrates the possibility of modeling the overall process of F101 engine repair, and demonstrates ways to achieve global optimization.

Appendix A. Work Control Document Summary

Appendix A-1. Work Control Document

Ind.	WCD	RCC	EC	SC	RCC Description
14-01	60612R	MEPCA	C01	AC	CHEM CLEAN ENG COMP
14-02	60612R	MEPCB	G01	AI	INSP/WCD/DECOS ENG C
14-03	60612R	MEPCN	I05	BI	X-RAY/TCR NDI/ECII
14-04	60612R	MEPMW	I07	BI	L/S-H/S COMPRESSOR
14-05	60612R	MEPMW	I07	BB	L/S-H/S COMPRESSOR
02-01	60635R	MEPCA	C01	AC	CHEM CLEAN ENG COMP
02-02	60635R	MEPCB	G01	AI	INSP/WCD/DECOS ENG C
02-03	60635R	MEPCN	I03	BI	X-RAY/TCR NDI/ECII
02-04	60635R	MEPMV	I07	BI	TURBINE DISK/SHAFT
02-05	60635R	MEPMV	G01	BB	TURBINE DISK/SHAFT
02-06	60635R	MEPMS	I08	AI	TURBINE SHAFT
02-07	60635R	MEPMV	I07	BB	TURBINE DISK/SHAFT
02-08	60635R	MEPCN	I08	BI	X-RAY/TCR NDI/ECII
02-09	60635R	MEPMV	G01	BI	TURBINE DISK/SHAFT
02-10	60635R	MEPCG	U07	AC	BLAST/SURFACE PREP
02-11	60635R	MEPMV	L01	BJ	TURBINE DISK/SHAFT
02-12	60635R	MEPCH	P12	CR	PLATING A/C ENG PART
02-13	60635R	MEPCH	G19	BR	PLATING A/C ENG PART
02-14	60635R	MEPMS	I08	AI	TURBINE SHAFT
02-15	60635R	MEPCN	I03	BI	X-RAY/TCR NDI/ECII
02-16	60635R	MEPCI	T03	AI	PLASMA SPRAY
02-17	60635R	MEPCI	G01	AB	PLASMA SPRAY
02-18	60635R	MEPCI	U01	AC	PLASMA SPRAY
02-19	60635R	MEPCI	T03	A2	PLASMA SPRAY
02-20	60635R	MEPCI	G01	A2	PLASMA SPRAY
02-21	60635R	MEPCH	G19	BR	PLATING A/C ENG PART
02-22	60635R	MEPMV	L01	BJ	TURBINE DISK/SHAFT
02-23	60635R	MEPMV	I07	BI	TURBINE DISK/SHAFT
02-24	60635R	MEPCA	C05	AC	CHEM CLEAN ENG COMP
02-25	60635R	MEPMV	I07	AI	TURBINE DISK/SHAFT
04-01	60636R	MEPCA	C04	AC	CHEM CLEAN ENG COMP
04-02	60636R	MEPCB	G01	AI	INSP/WCD/DECOS ENG C
04-03	60636R	MEPCG	U10	AC	BLAST/SURFACE PREP
04-04	60636R	MEPCN	I05	BI	X-RAY/TCR NDI/ECII
04-05	60636R	MEPCN	I06	BI	X-RAY/TCR NDI/ECII
04-06	60636R	MEPMV	I07	BI	TURBINE DISK/SHAFT
04-07	60636R	MEPMV	G01	BB	TURBINE DISK/SHAFT
04-08	60636R	MEPMV	I07	BI	TURBINE DISK/SHAFT
04-09	60636R	MEPMS	I08	AI	TURBINE SHAFT
04-10	60636R	MEPMV	I07	BB	TURBINE DISK/SHAFT
04-11	60636R	MEPMS	I08	AI	TURBINE SHAFT
04-12	60636R	MEPMV	I11	BI	TURBINE DISK/SHAFT
04-13	60636R	MEPMV	G01	BI	TURBINE DISK/SHAFT
12-01	60637R	MEPCA	C01	AC	CHEM CLEAN ENG COMP
12-02	60637R	MEPCB	G01	AI	INSP/WCD/DECOS ENG C

Ind.	WCD	RCC	EC	SC	RCC Description
12-03	60637R	MEPCN	I03	BI	X-RAY/TCR NDI/ECII
12-04	60637R	MEPMV	I07	AI	TURBINE DISK/SHAFT
12-05	60637R	MEPCN	I15	BI	X-RAY/TCR NDI/ECII
12-06	60637R	MEPMV	G01	AB	TURBINE DISK/SHAFT
12-07	60637R	MEPCN	I08	BI	X-RAY/TCR NDI/ECII
12-08	60637R	MEPMV	G01	AB	TURBINE DISK/SHAFT
12-09	60637R	MEPCH	G01	AB	PLATING A/C ENG PART
12-10	60637R	MEPCH	P12	AR	PLATING A/C ENG PART
12-11	60637R	MEPMV	G01	AB	TURBINE DISK/SHAFT
12-12	60637R	MEPMV	G04	AJ	TURBINE DISK/SHAFT
12-13	60637R	MEPMV	G01	AB	TURBINE DISK/SHAFT
12-14	60637R	MEPCN	I03	BI	X-RAY/TCR NDI/ECII
12-15	60637R	MEPCH	G01	AB	PLATING A/C ENG PART
12-16	60637R	MEPCH	P01	AB	PLATING A/C ENG PART
12-17	60637R	MEPMV	G01	AB	TURBINE DISK/SHAFT
12-18	60637R	MEPMV	G04	AJ	TURBINE DISK/SHAFT
12-19	60637R	MEPMV	G01	AB	TURBINE DISK/SHAFT
12-20	60637R	MEPMV	D03	AJ	TURBINE DISK/SHAFT
12-21	60637R	MEPMV	G01	AB	TURBINE DISK/SHAFT
05-01	60659R	MEPBH	C05	AC	BLADE CLEAN/SURF ENH
05-02	60659R	MEPBE	C02	AC	SURFACE PREP BLADES
05-03	60659R	MEPBF	I07	AI	BLADE FPI/NDI INSPEC
05-04	60659R	MEPBG	G01	AB	REWRK FAN/TURB/COMP
18-01	60660R	MEPCA	C05	AC	CHEM CLEAN ENG COMP
18-02	60660R	MEPCB	G01	AI	INSP/WCD/DECOS ENG C
18-03	60660R	MEPMV	I07	BJ	TURBINE DISK/SHAFT
11-01	60661R	MEPCA	C01	AC	CHEM CLEAN ENG COMP
11-02	60661R	MEPCB	G01	AI	INSP/WCD/DECOS ENG C
11-03	60661R	MEPCB	I07	AI	INSP/WCD/DECOS ENG C
11-04	60661R	MEPCG	U01	AC	BLAST/SURFACE PREP
11-05	60661R	MEPCN	I03	BI	X-RAY/TCR NDI/ECII
11-06	60661R	MEPMV	I07	BI	TURBINE DISK/SHAFT
11-07	60661R	MEPMV	G01	BB	TURBINE DISK/SHAFT
11-08	60661R	MEPCN	I08	BI	X-RAY/TCR NDI/ECII
11-09	60661R	MEPMV	I07	BI	TURBINE DISK/SHAFT
06-01	60662R	MEPCA	C01	AC	CHEM CLEAN ENG COMP
06-02	60662R	MEPCB	G01	AI	INSP/WCD/DECOS ENG C
06-03	60662R	MEPCB	I07	AI	INSP/WCD/DECOS ENG C
06-04	60662R	MEPCN	I03	CI	X-RAY/TCR NDI/ECII
06-05	60662R	MEPMP	I07	AI	CNC MACHINING
06-06	60662R	MEPMK	I15	AI	HOURGLASS/HEAVY MACHINING
06-07	60662R	MEPMP	L04	AJ	CNC MACHINING
06-08	60662R	MEPMR	G01	AJ	CASE REWORK
06-09	60662R	MEPMP	I07	AJ	CNC MACHINING
06-10	60662R	MEPCN	I03	CI	X-RAY/TCR NDI/ECII
06-11	60662R	MEPMR	C04	AC	CASE REWORK
06-12	60662R	MEPCJ	A14	AK	HEAT TREAT SHOP
06-13	60662R	MEPWG	G01	AB	GENERAL REWORK
06-14	60662R	MEPCH	G01	BB	PLATING A/C ENG PART
06-15	60662R	MEPCH	P02	BR	PLATING A/C ENG PART
06-16	60662R	MEPCH	G01	BB	PLATING A/C ENG PART

Ind.	WCD	RCC	EC	SC	RCC Description
06-17	60662R	MEPCH	C03	BC	PLATING A/C ENG PART
06-18	60662R	MEPCH	A09	BR	PLATING A/C ENG PART
06-19	60662R	MEPWB	I07	AB	GENERAL WELDING
06-20	60662R	MEPWB	G01	AB	GENERAL WELDING
06-21	60662R	MEPWB	C06	AB	GENERAL WELDING
06-22	60662R	MEPWB	W14	AB	GENERAL WELDING
06-23	60662R	MEPWB	W07	AB	GENERAL WELDING
06-24	60662R	MEPWB	W14	AB	GENERAL WELDING
06-25	60662R	MEPWB	W07	AB	GENERAL WELDING
06-26	60662R	MEPWB	W14	AB	GENERAL WELDING
06-27	60662R	MEPCJ	A16	AK	HEAT TREAT SHOP
06-28	60662R	MEPWB	I22	AI	GENERAL WELDING
06-29	60662R	MEPWB	W14	AB	GENERAL WELDING
06-30	60662R	MEPCJ	A16	AK	HEAT TREAT SHOP
06-31	60662R	MEPCJ	A06	AK	HEAT TREAT SHOP
06-32	60662R	MEPWG	I22	AI	GENERAL REWORK
06-33	60662R	MEPMK	I15	AI	HOURGLASS/HEAVY MACHINING
06-34	60662R	MEPMP	G21	AJ	CNC MACHINING
06-35	60662R	MEPMP	I07	AI	CNC MACHINING
06-36	60662R	MEPME	E03	AJ	SEAL SHOP
06-37	60662R	MEPMP	G01	AB	CNC MACHINING
06-38	60662R	MEPMP	C05	AB	CNC MACHINING
06-39	60662R	MEPMK	I15	AI	HOURGLASS/HEAVY MACHINING
06-40	60662R	MEPCN	I03	CI	X-RAY/TCR NDI/ECII
06-41	60662R	MEPMP	C05	AB	CNC MACHINING
06-42	60662R	MEPMP	I07	AI	CNC MACHINING
06-43	60662R	MEPMP	Q02	AI	CNC MACHINING
01-01	60663R	MEPCA	C01	AC	CHEM CLEAN ENG COMP
01-02	60663R	MEPCB	G01	AI	INSP/WCD/DECOS ENG C
01-03	60663R	MEPCG	U10	AC	BLAST/SURFACE PREP
01-04	60663R	MEPCB	I07	AB	INSP/WCD/DECOS ENG C
01-05	60663R	MEPCN	I03	BI	X-RAY/TCR NDI/ECII
01-06	60663R	MEPMV	I07	BI	TURBINE DISK/SHAFT
01-07	60663R	MEPMV	G01	BB	TURBINE DISK/SHAFT
01-08	60663R	MEPCN	I08	BI	X-RAY/TCR NDI/ECII
01-09	60663R	MEPCN	G01	AB	X-RAY/TCR NDI/ECII
01-10	60663R	MEPCN	I16	AI	X-RAY/TCR NDI/ECII
01-11	60663R	MEPCN	I08	BI	X-RAY/TCR NDI/ECII
01-12	60663R	MEPCH	G01	BR	PLATING A/C ENG PART
01-13	60663R	MEPCH	I07	BI	PLATING A/C ENG PART
08-01	60665R	MEPCA	C01	AC	CHEM CLEAN ENG COMP
08-02	60665R	MEPCB	G01	AI	INSP/WCD/DECOS ENG C
08-03	60665R	MEPCB	I07	AI	INSP/WCD/DECOS ENG C
08-04	60665R	MEPCN	I03	BI	X-RAY/TCR NDI/ECII
08-05	60665R	MEPMV	I07	AI	TURBINE DISK/SHAFT
08-06	60665R	MEPMV	G01	AB	TURBINE DISK/SHAFT
08-07	60665R	MEPCN	I08	BI	X-RAY/TCR NDI/ECII
08-08	60665R	MEPCN	I07	BI	X-RAY/TCR NDI/ECII
10-01	60666R	MEPCA	C01	AC	CHEM CLEAN ENG COMP
10-02	60666R	MEPCB	G01	AI	INSP/WCD/DECOS ENG C
10-03	60666R	MEPCB	I07	AI	INSP/WCD/DECOS ENG C

Ind.	WCD	RCC	EC	SC	RCC Description
10-04	60666R	MEPCN	I03	BI	X-RAY/TCR NDI/ECII
10-05	60666R	MEPMV	I07	BI	TURBINE DISK/SHAFT
10-06	60666R	MEPCN	I08	BI	X-RAY/TCR NDI/ECII
10-07	60666R	MEPMV	I07	BI	TURBINE DISK/SHAFT
03-01	60667R	MEPCA	C01	AC	CHEM CLEAN ENG COMP
03-02	60667R	MEPCB	G01	AI	INSP/WCD/DECOS ENG C
03-03	60667R	MEPCG	U10	AC	BLAST/SURFACE PREP
03-04	60667R	MEPCB	I07	AI	INSP/WCD/DECOS ENG C
03-05	60667R	MEPCN	I03	BI	X-RAY/TCR NDI/ECII
03-06	60667R	MEPMV	I07	BI	TURBINE DISK/SHAFT
03-07	60667R	MEPMV	G01	BB	TURBINE DISK/SHAFT
03-08	60667R	MEPCN	I08	BI	X-RAY/TCR NDI/ECII
03-09	60667R	MEPCN	I07	AI	X-RAY/TCR NDI/ECII
03-10	60667R	MEPMW	G17	BJ	L/S-H/S COMPRESSOR
03-11	60667R	MEPCA	C01	AC	CHEM CLEAN ENG COMP
03-12	60667R	MEPCN	G01	AB	X-RAY/TCR NDI/ECII
03-13	60667R	MEPCN	I16	AI	X-RAY/TCR NDI/ECII
03-14	60667R	MEPCN	I07	AI	X-RAY/TCR NDI/ECII
03-15	60667R	MEPCN	G01	AB	X-RAY/TCR NDI/ECII
03-16	60667R	MEPCN	I07	AI	X-RAY/TCR NDI/ECII
13-01	60668R	MEPBH	C05	AC	BLADE CLEAN/SURF ENH
13-02	60668R	MEPBE	C02	AC	SURFACE PREP BLADES
13-03	60668R	MEPBG	I07	AI	REWRK FAN/TURB/COMP
13-04	60668R	MEPBG	G01	AB	REWRK FAN/TURB/COMP
09-01	60669R	MEPCA	C01	AC	CHEM CLEAN ENG COMP
09-02	60669R	MEPCA	C05	AC	CHEM CLEAN ENG COMP
09-03	60669R	MEPCB	G01	AI	INSP/WCD/DECOS ENG C
09-04	60669R	MEPCB	I07	AI	INSP/WCD/DECOS ENG C
09-05	60669R	MEPCN	I03	BI	X-RAY/TCR NDI/ECII
09-06	60669R	MEPMV	I07	BI	TURBINE DISK/SHAFT
09-07	60669R	MEPMV	G01	BB	TURBINE DISK/SHAFT
09-08	60669R	MEPCN	I08	BI	X-RAY/TCR NDI/ECII
09-09	60669R	MEPMV	I07	BI	TURBINE DISK/SHAFT
17-01	60673R	MEPCA	C05	AC	CHEM CLEAN ENG COMP
17-02	60673R	MEPCB	G01	AI	INSP/WCD/DECOS ENG C
17-03	60673R	MEPCG	U06	AC	BLAST/SURFACE PREP
17-04	60673R	MEPMV	I07	BI	TURBINE DISK/SHAFT
17-05	60673R	MEPMV	G01	BB	TURBINE DISK/SHAFT
07-01	60674R	MEPCA	C01	AC	CHEM CLEAN ENG COMP
07-02	60674R	MEPCB	G01	AI	INSP/WCD/DECOS ENG C
07-03	60674R	MEPCB	I07	AI	INSP/WCD/DECOS ENG C
07-04	60674R	MEPCN	I03	BI	X-RAY/TCR NDI/ECII
07-05	60674R	MEPMV	I07	AI	TURBINE DISK/SHAFT
07-06	60674R	MEPMV	G01	AB	TURBINE DISK/SHAFT
07-07	60674R	MEPMK	I15	AI	HOURGLASS/HEAVY MACHINING
07-08	60674R	MEPMV	I07	AI	TURBINE DISK/SHAFT
16-01	60675R	MEPCA	C01	AC	CHEM CLEAN ENG COMP
16-02	60675R	MEPCB	G01	AI	INSP/WCD/DECOS ENG C
16-03	60675R	MEPMW	I05	AI	L/S-H/S COMPRESSOR
16-04	60675R	MEPMW	I07	AI	L/S-H/S COMPRESSOR
15-01	60677R	MEPCA	C01	AC	CHEM CLEAN ENG COMP

Ind.	WCD	RCC	EC	SC	RCC Description
15-02	60677R	MEPCB	G01	AI	INSP/WCD/DECOS ENG C
15-03	60677R	MEPCN	I03	BI	X-RAY/TCR NDI/ECII
15-04	60677R	MEPMV	I07	AI	TURBINE DISK/SHAFT

Appendix A-2. Indication of Shared Equipments

		MEPBE	MEPBF	MEPBG	MEPBH	MEPCA	MEPCB	MEPCG	MEPCH	MEPCI	MEPCJ	MEPCN	MEPME	MEPMK	MEPMP	MEPMR	MEPMS	MEPMV	MEPMW	MEPWB	MEPWG
1	A06										1										
2	A09								1												
3	A14										1										
4	A16										1										
5	C01					1															
6	C02	1																			
7	C03								1												
8	C04					1										1					
9	C05				1	1									1						
10	C06																			1	
11	D03																	1			
12	E03												1								
13	G01			1			1		1	1		1			1	1		1	1	1	1
14	G04																	1			
15	G17																		1		
16	G19								1												
17	G21														1						
18	I03											1									
19	I05											1							1		
20	I06											1									
21	I07		1	1			1		1			1			1			1	1	1	
22	I08											1					1				
23	I11																	1			
24	I15											1		1							
25	I16											1									
26	I22																			1	1
27	L01																	1			
28	L04														1						
29	P01								1												
30	P02								1												
31	P12								1												
32	Q02														1						
33	T03									1											
34	U01							1		1											
35	U06							1													
36	U07							1													
37	U10							1													
38	W07																			1	

Note: Equipment shared by a specific RCC is indicated as 1.

Appendix A-3. Indication of Shared Skills

		MEPBE	MEPBF	MEPBG	MEPBH	MEPCA	MEPCB	MEPCG	MEPCH	MEPCI	MEPCJ	MEPCN	MEPME	MEPMK	MEPMP	MEPMR	MEPMS	MEPMV	MEPMW	MEPWB	MEPWG
1	A2									1											
2	AB			1			1		1	1		1			1			1		1	1
3	AC	1			1	1		1		1						1				1	
4	AI		1	1			1			1		1		1	1		1	1	1	1	1
5	AJ												1		1	1		1			
6	AK										1										
7	AR								1												
8	BB								1									1	1		
9	BC								1												
10	BI								1			1						1	1		
11	BJ																	1	1		
12	BR								1												
13	CI											1									
14	CR								1												

Note: Labor skill shared by a specific RCC is indicated as 1.

Appendix A-4. Parts vs. RCCs

RCC	P# 1	P# 2	P# 3	P# 4	P# 5	P# 6	P# 7	P# 8	P# 9	P# 10	P# 11	P# 12	P# 13	P# 14	P# 15	P# 16	P# 17	P# 18
BE					1								1					
BF					1													
BG					1								2					
BH					1								1					
CA	1	2	2	1		1	1	1	2	1	1	1		1	1	1	1	1
CB	2	1	2	1		2	2	2	2	2	2	1		1	1	1	1	1
CG	1	1	1	1							1						1	
CH	2	3				5						4						
CI		5																
CJ						4												
CN	5	3	8	2		3	1	3	2	2	2	4		1	1			
ME						1												
MK						3	1											
MP						10												
MR						2												
MS		2		2														
MV	2	8	2	6			3	2	3	2	3	11			1		2	1
MW			1											2		2		
WB						10												
WG						2												
# Ops	**13**	**25**	**16**	**13**	**4**	**43**	**8**	**8**	**9**	**7**	**9**	**21**	**4**	**5**	**4**	**4**	**5**	**3**

Note: This table shows the number of operations performed within each RCC for each type of part.

Appendix A-5. Parts vs. Equipment

EC	P# 1	P# 2	P# 3	P# 4	P# 5	P# 6	P# 7	P# 8	P# 9	P# 10	P# 11	P# 12	P# 13	P# 14	P# 15	P# 16	P# 17	P# 18
A06						1												
A09						1												
A14						1												
A16						1												
C01	1	1	2			1	1	1	1	1	1	1		1	1	1		
C02					1								1					
C03						1												
C04				1		1												
C05		1			1	2			1				1				1	1
C06						1												
D03												1						
E03						1												
G01	4	5	4	3	1	7	2	2	2	1	2	10	1	1	1	1	2	1
G04												2						
G17			1															
G19		2																
G21						1												
I03	1	2	1			3	1	1	1	1	1	2			1			
I05				1										1		1		
I06	1			1														
I07	3	4	5	3	1	6	3	3	3	3	3	1	1	2	1	1	1	1
I08	2	3	1	2				1	1	1	1	1						
I11				1														
I15						3	1					1						
I16			1			1												
I22						2												
L01		2																
L04						1												
P01												1						
P02						1												
P12		1										1						
Q02						1												
T03		2																
U01		1		1							1							
U06																	1	
U07		1																
U10	1		1															
W07						2												
W14						4												
# Ops	**13**	**25**	**16**	**13**	**4**	**43**	**8**	**8**	**9**	**7**	**9**	**21**	**4**	**5**	**4**	**4**	**5**	**3**

Note: This table shows the total number of times that a specific type of equipment requested by each type of part.

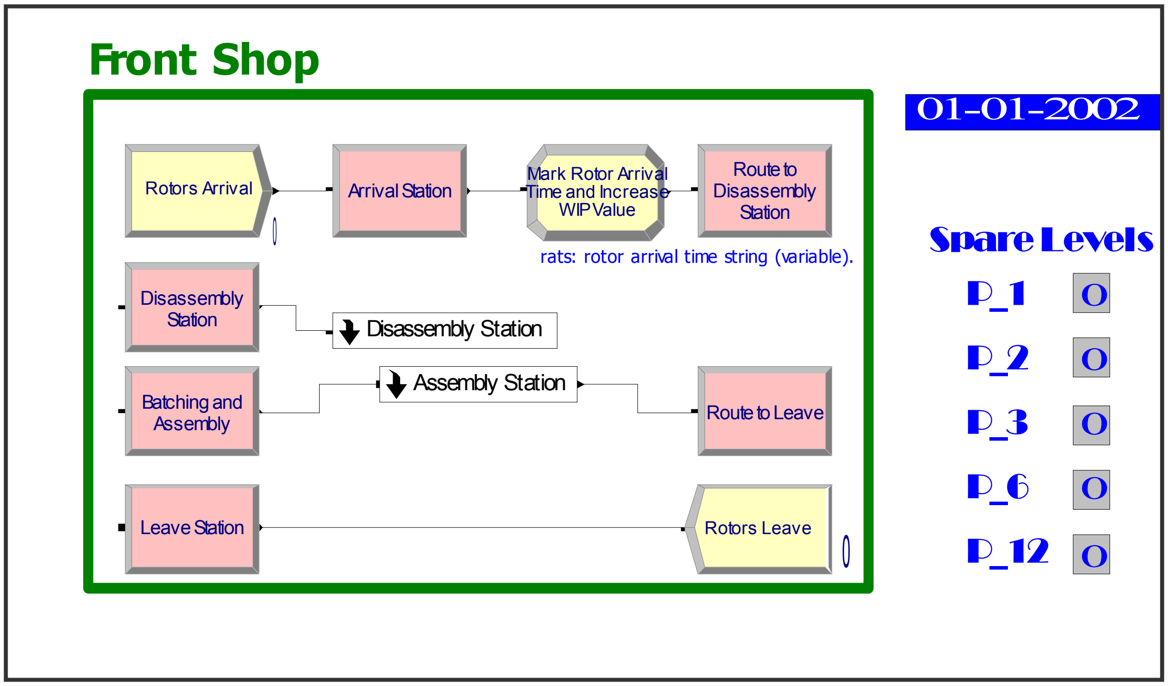
Appendix A-6. Parts vs. Labor Skills

SC	P# 1	P# 2	P# 3	P# 4	P# 5	P# 6	P# 7	P# 8	P# 9	P# 10	P# 11	P# 12	P# 13	P# 14	P# 15	P# 16	P# 17	P# 18
A2		2																
AB	2	1	2		1	13	1	1				10	1					
AC	2	4	3	2	2	2	1	1	2	1	2	1	2	1	1	1	2	1
AI	2	5	6	3	1	11	5	3	2	2	2	2	1	1	2	3	1	1
AJ						5						3						
AK						4												
AR												1						
BB	1	2	1	2		2			1		1			1			1	
BC						1												
BI	5	6	3	6			1	3	4	4	4	4		2	1		1	
BJ		2	1															1
BR	1	2				2												
CI						3												
CR		1																
# Ops	**13**	**25**	**16**	**13**	**4**	**43**	**8**	**8**	**9**	**7**	**9**	**21**	**4**	**5**	**4**	**4**	**5**	**3**

Note: This table shows the total number of times that a specific type of labor skill requested by each type of part.

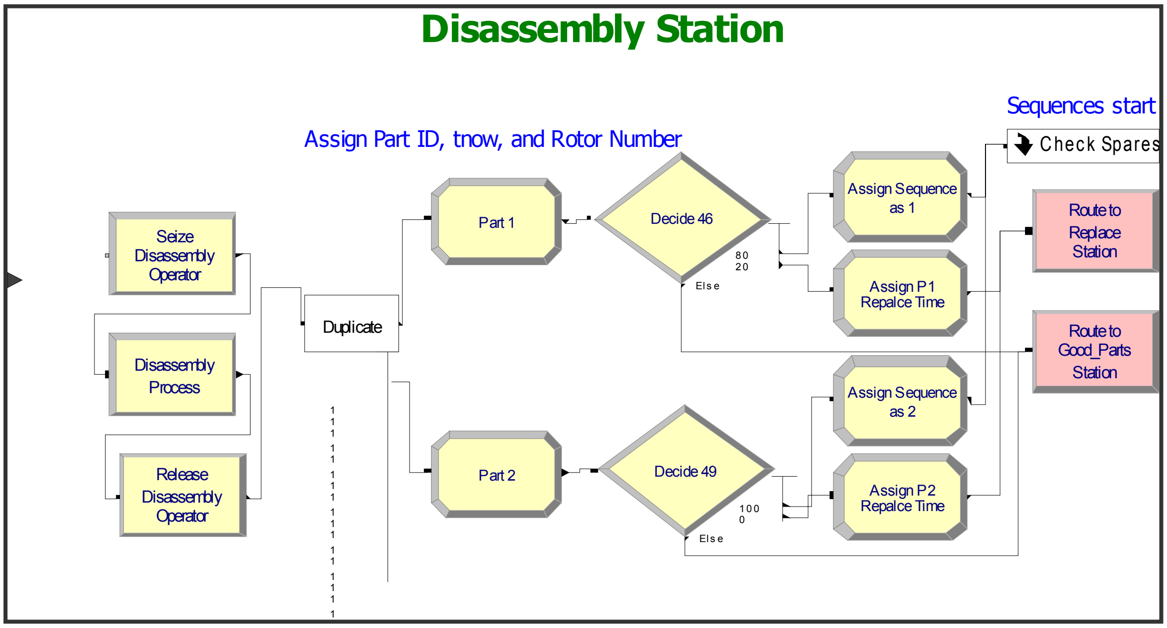
Appendix B. Arena Model

Appendix B-1. Front Shop



Note: Two sub-models in the Front Shop are Disassembly and Assembly Stations. On the right hand side, the current spare levels available of these critical parts are shown concurrently.

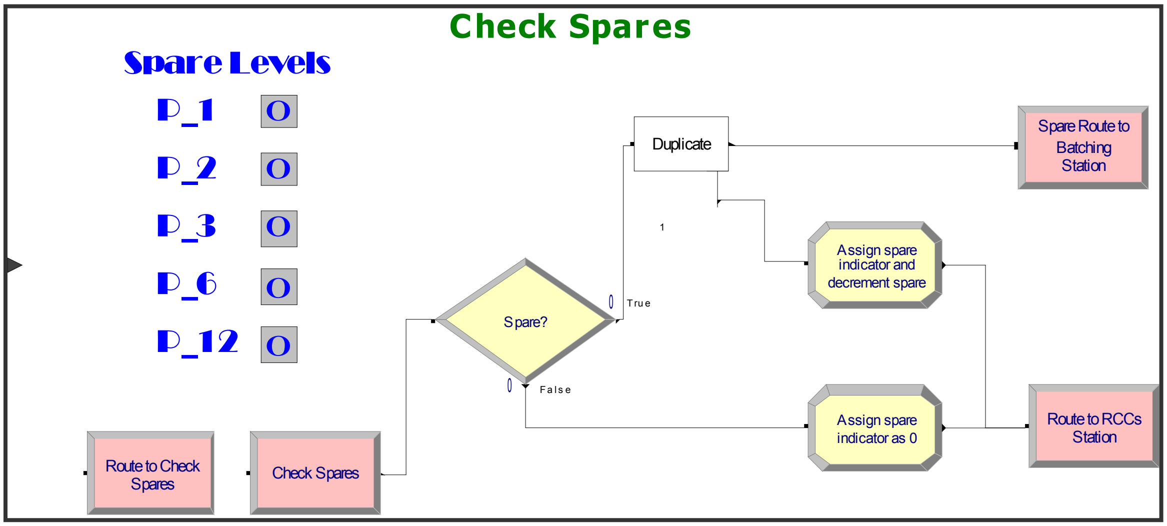
Appendix B-2. Disassembly Sub-model



Note:

- The rotor entity is duplicated to 18 part entities; Part ID #, Arrival Index, tnow, and Entity Picture are assigned to each part entity.
- According to the percentages shown in Table 2, each part is repaired, replaced, or directly sent to the assembling queue.
- The Check Spares sub-sub-model is illustrated in Appendix B-3.

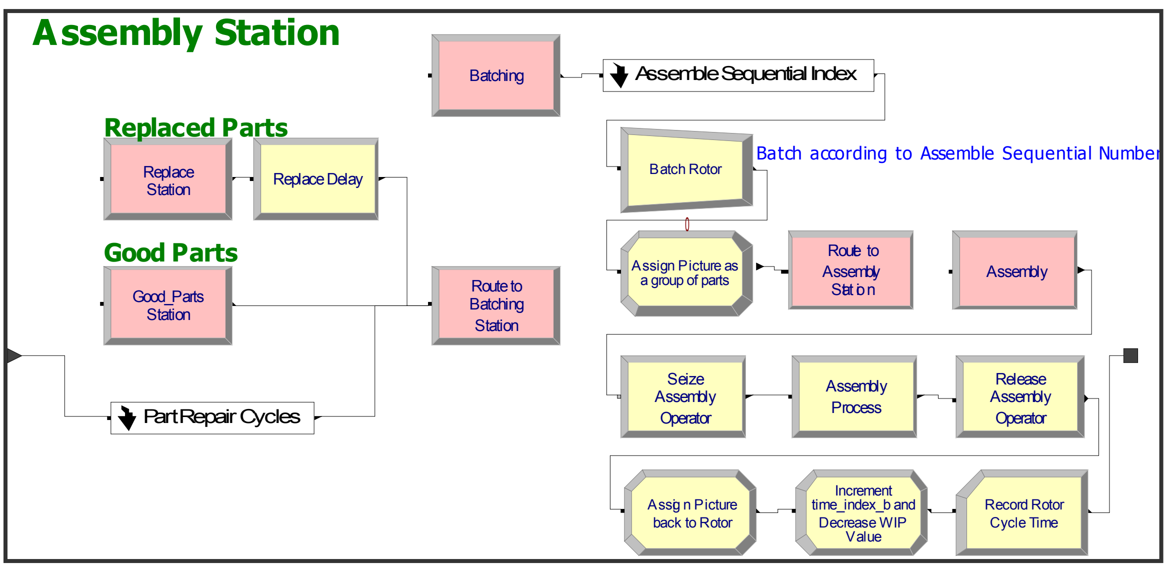
Appendix B-3 Check Spares Sub-sub-model



Note:

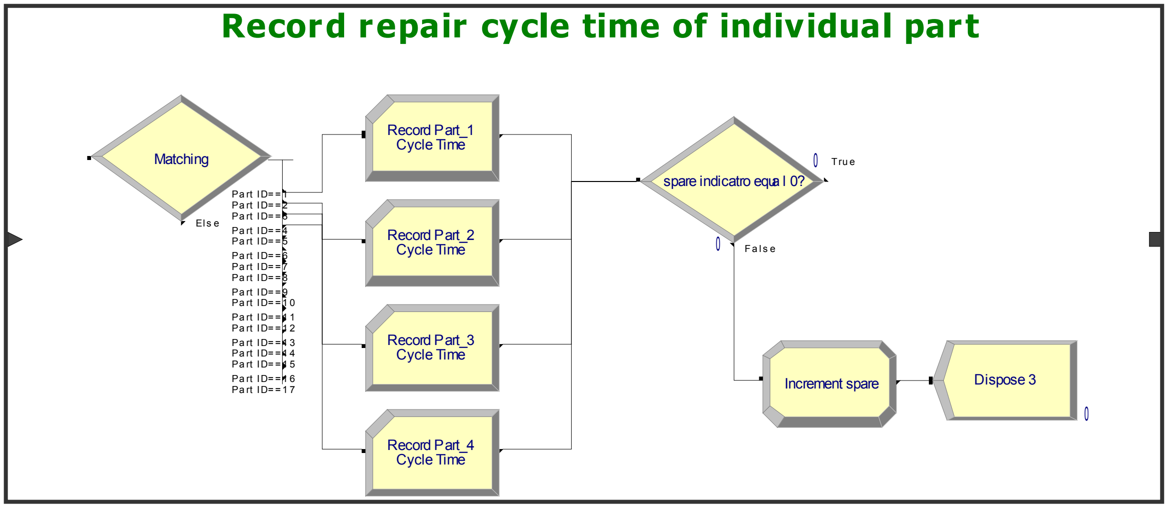
- If a part has a spare, it triggers a spare be sent to the Assembly Station, and itself is sent to the Back Shop for repairing.
- As illustrated in Appendix B-5, after repairing, those repairing parts with their spare indicator value assigned as 1 are looped back to the spare pool.

Appendix B-4. Batching & Assembly Sub-model



Note: Parts are put together as a set of assembling parts according to their assemble sequential index values assigned in the Assemble Sequential Index sub-model.

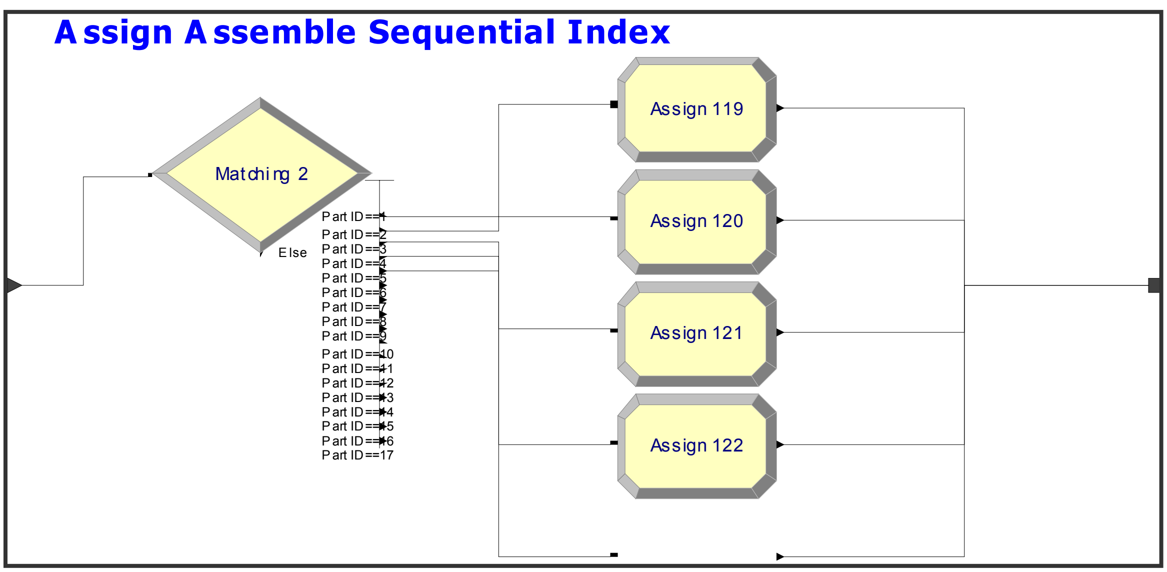
Appendix B-5. Record Repair Cycles Sub-sub-model



Note:

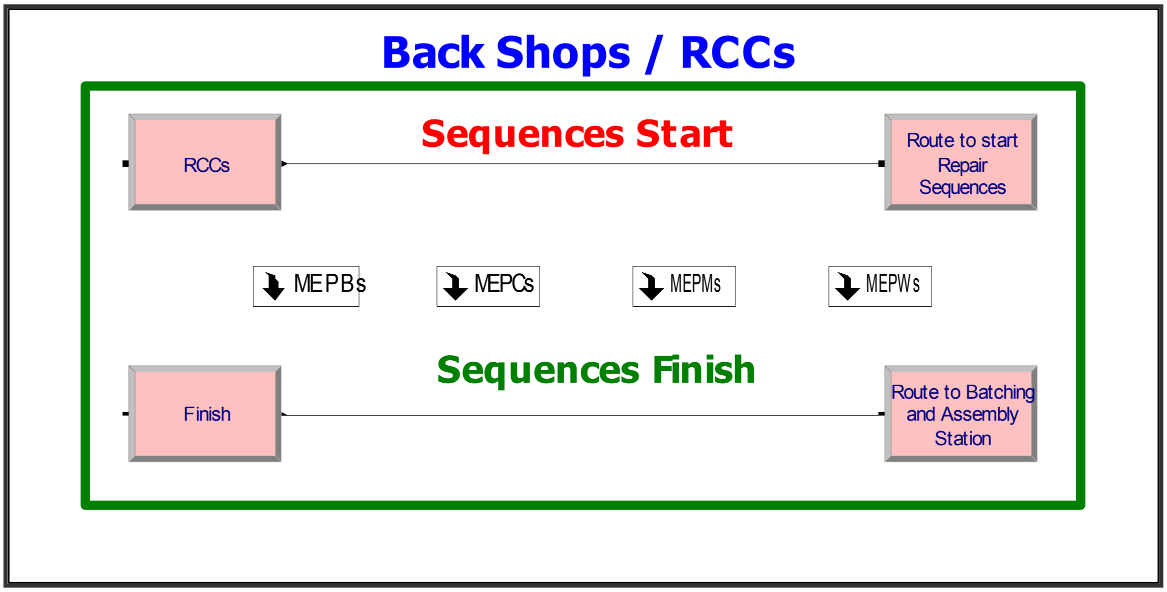
- Repair cycle time of each part is recorded according to its specific Part ID #.
- If a part triggered a spare to be used early in the Disassembly Station, it will be looped back to the spare pool and the specific spare will be incremented; else, it will be sent to the batching station.

Appendix B-6. Assign Assemble Sequential Index Sub-sub-model



Note: There are 18 incrementing Assemble Sequential Index, one for each part type. As soon as there is one part arriving from each of these 18 types, they are batched as a set of assembling parts.

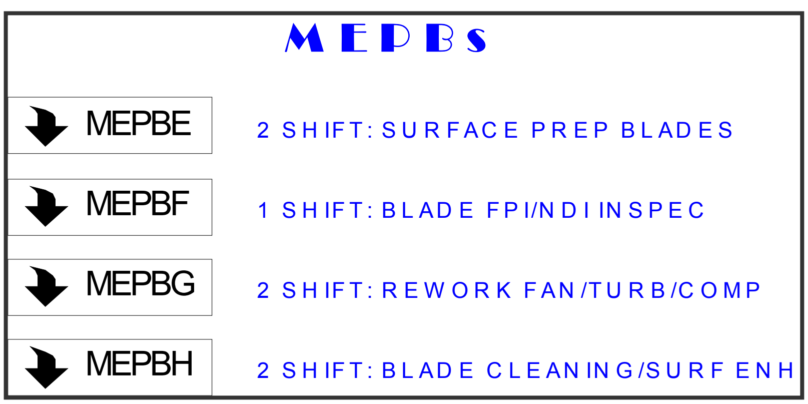
Appendix B-7. Back Shop



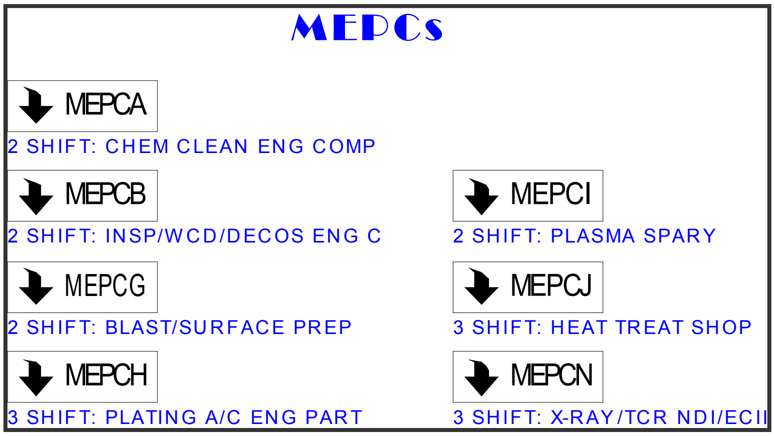
Note:

- There are 20 RCCs in the Back Shop. A repairing part is processed according to the procedures defined by its specified sequence. After all the operations are done, the part will be routed back to the Assembly Station.
- For the convenience of model building, the RCCs are clustered to 4 sub-models as illustrated in Appendices B-8, B-9, B-10, and B-11.

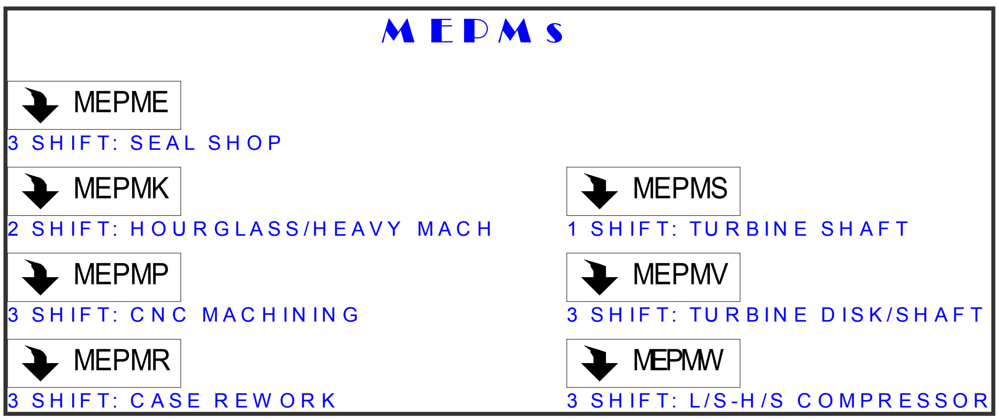
Appendix B-8. MEPBs Sub-models



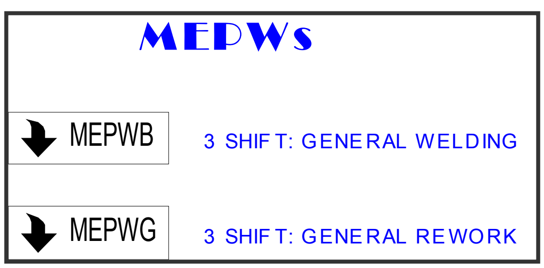
Appendix B-9. MEPCs Sub-models



Appendix B-10. MEPMs Sub-models



Appendix B-11. MEPWs Sub-models



Appendix C. Times Between LPT Rotor Arrivals

Rotor Assembly	Arrival Date	Time Between Arrival (days)
9607342	1-Sep	0
9607348	1-Sep	0
9607367	1-Sep	0
9626934	9-Sep	8
9626937	9-Sep	0
9652633	15-Sep	6
9652643	15-Sep	0
9768712	19-Oct	34
9750874	19-Oct	0
9768707	19-Oct	0
9768721	19-Oct	0
9768736	19-Oct	0
9797276	30-Oct	11
9797400	1-Nov	2
9797403	1-Nov	0
9797413	1-Nov	0
9804419	3-Nov	2
9822788	6-Nov	3
9836668	13-Nov	7
9836673	13-Nov	0
9867052	23-Nov	10
9883573	4-Dec	11
9968492	5-Jan	32
9970412	8-Jan	3
10000625	16-Jan	8
10000632	16-Jan	0
10022669	22-Jan	6
10023016	22-Jan	0
10026071	23-Jan	1
10045799	29-Jan	6
10045800	29-Jan	0
10045804	29-Jan	0
10045807	29-Jan	0
10050990	30-Jan	1
10050997	30-Jan	0
10051002	30-Jan	0
10051081	30-Jan	0
10051088	30-Jan	0
10051101	30-Jan	0
10125616	21-Feb	22
10125621	21-Feb	0
10134372	23-Feb	2
10134376	23-Feb	0
10134382	23-Feb	0
10141131	26-Feb	3
10146403	27-Feb	1
10160274	3-Mar	4
10160275	3-Mar	0
10160276	3-Mar	0
10180455	9-Mar	6
10196581	14-Mar	5
10235581	28-Mar	14
10239075	29-Mar	1

Appendix D. Linear Programming Optimization Spreadsheets

FIFO / Cycle Time

Factor	Low	Middle	High			(L+H)/2	(L-H)/2
P1	2	5	8			5	3
P6	3	6	9			6	3

Factor	Natural	Coded
P1	7	0.6666667
P6	8	0.6666667

Term	Intercept	P1	P6	P1P6	$P1^2$	$P6^2$	Cycle
Coef.	13.026814	-0.646017	-1.53655	-0.18605	0.5898214	1.2006214	
Coded		0.6667	0.6667	0.4444	0.4444	0.4444	12.285

FIFO / WIP Investment

Factor	Low	Middle	High			(L+H)/2	(L-H)/2
P1	2	5	8			5	3
P6	3	6	9			6	3

Factor	Natural	Coded
P1	3	-0.666667
P6	7	0.3333333

Term	Intercept	P1	P6	P1P6	$P1^2$	$P6^2$	WIP
Coef.	403888.07	27789.333	-29246.33	-6902.75	19541.357	30512.357	
Coded		-0.6667	0.3333	-0.2222	0.4444	0.1111	389,222.325

FIFO / Cycle Time & WIP Investment (MOLP)

Factor	Low	Middle	High		(L+H)/2	(L-H)/2
P1	2	5	8		5	3
P6	3	6	9		6	3

Factor	Natural	Coded
P1	5	0
P6	8	0.666666667

Cycle

Term	Intercept	P1	P6	P1P6	$P1^2$	$P6^2$
Coef.	13.026814	-0.646017	-1.53655	-0.18605	0.5898214	1.2006214
Coded		0.0000	0.6667	0.0000	0.0000	0.4444

WIP

Term	Intercept	P1	P6	P1P6	$P1^2$	$P6^2$
Coef.	403888.07	27789.333	-29246.33	-6902.75	19541.357	30512.357
Coded		0.0000	0.6667	0.0000	0.0000	0.4444

	Suggested Value	Target Value	% Deviation	Weight	Weighted % Deviation	Objective MiniMax
Cycle	12.536	12.2848	2.04%	1	2.04%	2.24%
WIP	397,951.564	389,222.33	2.24%	1	2.24%	

SPTF / Cycle Time

Factor	Low	Middle	High			(L+H)/2	(L-H)/2
P1	2	5	8			5	3
P6	3	6	9			6	3

Factor	Natural	Coded
P1	7	0.66666667
P6	9	1

Term	Intercept	P1	P6	P1P6	$P1^2$	$P6^2$	Cycle
Coef.	13.422829	-0.629317	-1.459667	-0.4262	0.7204929	0.6644429	
Coded		0.6667	1.0000	0.6667	0.4444	1.0000	12.244

SPTF LP / WIP Investment

Factor	Low	Middle	High			(L+H)/2	(L-H)/2
P1	2	5	8			5	3
P6	3	6	9			6	3

Factor	Natural	Coded
P1	3	-0.66666667
P6	8	0.66666667

Term	Intercept	P1	P6	P1P6	$P1^2$	$P6^2$	WIP
Coef.	419886.79	28149.833	-28322	-10098.75	17787.429	14890.929	
Coded		-0.6667	0.6667	-0.4444	0.4444	0.4444	401,250.949

SPTF / Cycle Time & WIP Investment (MOLP)

Factor	Low	Middle	High		(L+H)/2	(L-H)/2
P1	2	5	8		5	3
P6	3	6	9		6	3

Factor	Natural	Coded
P1	5	0
P6	9	1

Cycle

Term	Intercept	P1	P6	P1P6	$P1^2$	$P6^2$
Coef.	13.422829	-0.629317	-1.459667	-0.4262	0.7204929	0.6644429
Coded		0.0000	1.0000	0.0000	0.0000	1.0000

WIP

Term	Intercept	P1	P6	P1P6	$P1^2$	$P6^2$
Coef.	419886.79	28149.833	-28322	-10098.75	17787.429	14890.929
Coded		0.0000	1.0000	0.0000	0.0000	1.0000

	Suggested Value	Target Value	% Deviation	Weight	Weighted % Deviation	Objective MiniMax
Cycle	12.628	12.2441	3.13%	1	3.13%	3.13%
WIP	406,455.719	401250.95	1.30%	1	1.30%	

LAIVF / Cycle Time

Factor	Low	Middle	High			(L+H)/2	(L-H)/2
P1	2	5	8			5	3
P6	3	6	9			6	3

Factor	Natural	Coded
P1	7	0.66666667
P6	8	0.66666667

Term	Intercept	P1	P6	P1P6	$P1^2$	$P6^2$	Cycle
Coef.	12.934436	-0.443233	-1.246433	-0.167575	0.4473786	0.9080786	
Coded		0.6667	0.6667	0.4444	0.4444	0.4444	12.336

LAIVF / WIP Investment

Factor	Low	Middle	High			(L+H)/2	(L-H)/2
P1	2	5	8			5	3
P6	3	6	9			6	3

Factor	Natural	Coded
P1	2	-1
P6	7	0.33333333

Term	Intercept	P1	P6	P1P6	$P1^2$	$P6^2$	Cycle
Coef.	404875.57	34415.667	-22796	-3883	13865.857	21755.857	
Coded		-1.0000	0.3333	-0.3333	1.0000	0.1111	380,438.744

LAIVF / Cycle Time & WIP Investment (MOLP)

Factor	Low	Middle	High		(L+H)/2	(L-H)/2
P1	2	5	8		5	3
P6	3	6	9		6	3

Factor	Natural	Coded
P1	4	-0.333333333
P6	8	0.666666667

Cycle

Term	Intercept	P1	P6	P1P6	$P1^2$	$P6^2$
Coef.	12.934436	-0.443233	-1.246433	-0.167575	0.4473786	0.9080786
Coded		-0.3333	0.6667	-0.2222	0.1111	0.4444

WIP

Term	Intercept	P1	P6	P1P6	$P1^2$	$P6^2$
Coef.	404875.57	34415.667	-22796	-3883	13865.857	21755.857
Coded		-0.3333	0.6667	-0.2222	0.1111	0.4444

	Suggested Value	Target Value	% Deviation	Weight	Weighted % Deviation	Objective MiniMax
Cycle	12.742	12.3359	3.29%	1	3.29%	3.29%
WIP	390,279.157	380438.74	2.59%	1	2.59%	

Bibliography

Altiok, Tayfur and Melamed, Benjamin. *Simulation Modeling and Analysis with Arena*. Cyber Research, Inc. and Enterprise Technology Solutions, Inc., 2001.

Amouzegar, Mahyar A. "Expeditionary Operations," Air Force Journal of Logistics, Spring 2001, Vol. 25 Issue 1: 30.

Banks, Jerry and others. *Discrete-Event System Simulation*, 2nd ed. New Jersey: Prentice Hall Inc., 1999.

Blanchard, Benjamin S. *Logistics Engineering and Management*, 5th ed. New Jersey: Prentice Hall Inc., 1998.

Gaudette, Kevin J. *Material Requirements Planning in Air Force Depot-Level Maintenance*. MS thesis. AFIT/GIM/LAL/98S-2. Air Force Institute of Technology, Wright-Patterson AFB OH, September 1998 (AD-A354232).

Gogg, Thomas J. and others. "Applying Modeling and Critical Path Methods to the Re-engineering of Jet Engine Repairs at the Oklahoma City Air Logistics Center."

Gould, Lawrence S. "Introducing APS: Getting production in lock step with customer demand," Automotive Manufacturing & Production, May 1998, Vol.110 Issue 5: 54.

Kelton, David W. *Simulation with Arena*, 2nd ed. New York: McGraw-Hill Companies, Inc., 2002.

Kiebler, K. K. and others. *The Depot Repair Cycle Process: Opportunities for Business Practice Improvement*. McLean: Logistics Management Institute. 1996.

Krajewski, Lee J. and Ritzman, Larry P. *Operations Management*, 5th ed. Addison-Wesley Publishing Company, Inc., 1999.

Law, Averill M. and Kelton, David W. Simulation Modeling and Analysis, 3rd ed. New York: McGraw-Hill Companies, Inc., 2000.

Larvick, Jon A. "Wartime Spares," Air Force Journal of Logistics, Winter 2000, Vol.24 Issue 4: 2.

"Lean Air Force, A" IIE Solutions, Mar 2000, Vol.32 Issue 3: 14.

"Logistics Transformation: Advanced Planning and Scheduling (APS) Systems Overview" Headquarters USAF, 02 Aug 2001.

Montgomery, Douglas C. *Design and Analysis of Experiments*, 3rd ed. New York: Wiley, 1991.

Mooney, Kevin. *Improved Aviation Readiness and Inventory Reductions Through Repair Cycle Time Reductions Using Modeling and Simulation*. MS thesis. Naval Postgraduate School, Monterey CA, 1997 (AD-A345928).

Myers, Raymond H. and Montgomery, Douglas C. *Response Surface Methodology: Process and Product Optimization Using Designed Experiments*. New York: John Wiley & Sons, Inc., 1995.

Lehman, Ann and others. *JMP Start Statistics*. SAS Institute Inc., 2001.

Ragsdale, Cliff T. *Spreadsheet Modeling and Decision Analysis*, 3rd ed. Cincinnati: South-Western College Publishing, 2001.

Schultz, George. "A Portal Not a Process," APICS, Aug 2000.

Stearns, Dick E. *Logistics Simulations Metamodel for F404-GE-300 Engine Maintenance*. MS thesis. Naval Postgraduate School, Monterey CA, 1998 (AD-A359328).

Tripp, Robert S. "A Vision for agile combat support," Air Force Journal of Logistics, Winter 1999, Vol. 23 Issue 4: 6.

Turbide, David. "What is ERP?" Foundry Management & Technology, Aug 1999, Vol.127 Issue 8: 94.

Vashi, Vidyut H. and Bienstock, Carol C. "The use of response surface methodology to optimize logistics simulation models," Journal of Business Logistics, 1995, Vol.16 Issue 2: 197.

Warren David (Director, Defense Management Issues, National Security), "Depot Maintenance and Repair," FDCH Congressional Testimony, 23 Mar 2001.

Zettler, Michael E. (Lieutenant General, USAF). "Chief's Logistics Review," Air Force Journal of Logistics, Summer 2001, Vol. XXV Issue 2: 2.

McBride, Steven H. Industrial Engineer, HQ AFMC/LGPA, WPAFB OH. Personal interview. 16 Nov 2001.

Fryman, Mark A. Actuarial Mathematician, HQ AFMC/LGXM, WPAFB OH. Personal interview. 15 Oct 2001.

Vita

Captain Shenn-Rong Shyong was born in Taiwan, Republic of China. He graduated from Chung-Cheng Armed Forces Preparatory High School in 1989. From there he went on to the Chinese Military Academy (CMA). After finishing the first year at CMA, he was selected to attend the Virginia Military Institute (VMI). There, he was first exposed to the American culture and military education. By receiving a great amount of friendship and help from his classmates—*brother rats*, and members of the faculty, he managed to receive a Bachelor of Science degree in Computer Science in 1994.

Following graduation, 18 May 1994, Captain Shyong was assigned to the CMA as a platoon leader. On 16 June 1995, he was assigned to the Army Infantry 206th Division as a company executive officer, and reassigned as a company commander on 1 December 1995. After experiencing almost 2 years of recruitment training, he was assigned to the Ma-Tsu Defense Command as a company commander of an infantry company on 1 April 1997, and reassigned as the commander of the Command Headquarter Company on 1 Jun 1998. After being a company commander for 3 years and 4 months, he was assigned to the Intelligence Division of the Army General Headquarters as an international affairs liaison officer on 1 April 1999. In September 2000, Captain Shyong was selected to come to AFIT to pursue a Master of Science degree in Logistics Management. Upon graduation, 26 March 2002, he will be assigned back to the Army General Headquarters, Taiwan, Republic of China.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 074-0188

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From – To)*
26-03-2002	Master's Thesis	Mar 2001 – Mar 2002

4. TITLE AND SUBTITLE
ADVANCED PLANNING AND SCHEDULING IN THE UNITED STATE AIR FORCE DEPOT-LEVEL MAINTENANCE

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR (S)

Shyong, Shenn-Rong, CPT, Taiwan ROC Army

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAMES (S) AND ADDRESS (S)

Air Force Institute of Technology
Graduate School of Engineering and Management (AFIT/EN)
2950 P Street, Building 640
WPAFB OH 45433-7765

8. PERFORMING ORGANIZATION REPORT NUMBER
AFIT/GLM/ENS/02-16

9. SPONSORING/MONITORING AGENCY NAME (S) AND ADDRESS (ES)
Steven McBride, Industrial Engineer, HQ AFMC/LGPA, steven.mcbride@wpafb.af.mil
Mark Fryman, Actuarial Mathematician, HQ AFMC/LGXM, mark.fryman@wpafb.af.mil
WPAFB OH 45433-5006

10. SPONSOR/MONITOR'S ACRONYM (S)

11. SPONSOR/MONITOR'S REPORT NUMBER (S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

The development of Expeditionary Aerospace Force (EAF) operations requires rethinking of many Air Force functions. A Logistics Transformation Team, comprising Air Force and KPMG Consulting Incorporation personnel, is leading much of this transformation work. The very first step of the transformation initiatives is demand planning, which is the process of translating the war fighter's needs into executable logistics support plans and schedules. One important area that the demand planning focuses on is engine maintenance. This sub-mission is assigned to the F101 Engine Pathfinder Team, which is responsible for increasing the availability of the F101 engine. As part of the F101 Engine Pathfinder Team's effort, the focus of this thesis is to apply Modeling and Simulation (M&S), Response Surface Methodology (RSM), and Linear Programming (LP) to examine ways to reduce repair cycle time and work in process (WIP) investment for the F101 Low Pressure Turbine (LPT) rotor. We specifically evaluate a variety of job scheduling policies and spare levels.

15. SUBJECT TERMS
Air Force Depot Maintenance, Advanced Planning and Scheduling, Spare Level Analysis, Modeling and Simulation, LP Optimization, Response Surface Methodology

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
					Lt Col John O. Miller
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER *(Include area code)*
U	U	U	UU	106	(937) 255-6565, ext 4326 John.Miller@afit.af.edu

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39-18